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# SELECTION OF OPTIMAL FOREST HARVESTING SYSTEMS USING SHORTEST PATH NETWORK ANALYSIS

by

© GEORGE JOHN GARNER

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
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OF MASTER OF SCIENCE

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Selection of Optimal Forest Harvesting Systems Using Shortest Path Network Analysis" submitted by George John Garner in partial fulfilment of the requirements for the degree of Master of Science.

..........................

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# ABSTRACT

A methodology is described for identifying least-cost forest harvesting systems using shortest path network analysis. Components of the harvesting system are depicted in the form of a directed, acyclic network describing the sequence of alternative methods for satisfying the system's objectives. Nodes in the network represent completed operations (events). Arcs joining the nodes have values (durations) representing the cost of the event. The optimal (least-cost) and near-optimal forest harvesting systems are found by selecting and ranking by lowest total cost, different paths through the network.

A package of computer programs, written in BASIC for a Hewlett-Packard 9845B mini-computer, was developed for implementing the methodology. Routines aid in the definition of the network, and input of variables for each activity. Activity durations, measured in dollars per cubic metre of wood produced, were calculated from estimates of hourly costs and production for specified conditions. A before-tax cash flow model calculates activity costs on an annual equivalent cost basis. Productivity is determined using prediction equations to estimate activity cycle times for the conditions.

Sample application of the methodology is made to identify the cheapest system for logging and transporting tree-length material to a processing plant under Eastern Canadian conditions. The optimal system, a swather-type feller-primary transporter presently under development combined with roadside flail limbing, was significantly cheaper than alternative systems. The optimal system selected was found to be insensitive to fuel prices with fuel prices up to double present costs. Sensitivity analysis was also used to identify the least-cost harvesting systems under a range of tree diameters and stand volumes. The swather system was best under most tested conditions. However, with large tree sizes and low stand volumes, a system with a tractor-mounted shear, tracked grapple skidding and roadside flail limbing produced the lowest costs. A manual felling system produced the lowest costs with medium sized trees (24 cm DBH) and low stand volumes.

Shortest path network analysis was found to be a useful method of designing forest harvesting systems. The ability to identify both optimal and near-optimal systems is important when the differences between most systems are as small as those observed during the case study. The technique's biggest advantage is that many more alternatives than would usually be evaluated, can be examined quickly and in a manner which permits easy comprehension by non-technical personnel.

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# LIST OF SYMBOLS

SYMBOL DESCRIPTION

A - availability (decimal %)
APTD - average primary transport distance (m)
$CC_j$ - capital cost in year "j" ($/PMH)
CRF - capital recovery factor
CT - cycle time (cmin/cycle)
CW - wood cost ($/$m^3$)
DBH - diameter breast height (cm)
$D_{ij}$ - duration of path between nodes "i" and "j"
DIST - primary transport distance (m)
DISTRC1 - secondary transport distance on road class one
DISTRC2 - secondary transport distance on road class two
DISTRC3 - secondary transport distance on road class three
DR - depreciation rate (decimal %)
DSH - diameter stump height (cm)
EAC - equivalent annual cost ($/PMH)
EF - productivity adjustment factor for environmental conditions
FBF - fringe benefit factor
FC - fuel costs ($/PMH)
FP - fuel price ($/litre)
FS - coefficient of skidding friction
GHP - gross engine horespower (kW)
HCF - hydraulic complexity factor
HCOST - hourly cost for an activity ($/PMH)
HPROD - hourly productivity for an activity ($m^3$/PMH)
I - interest rate (decimal %)
IC - insurance costs ($/PMH)
LC - licencing costs ($/PMH)
LF - load factor
MA - mechanical availability (decimal %)
MC - manpower costs ($/PMH)
ML - merchantable tree-length (m)
MN - maximum number of nodes on a path

SYMBOL DESCRIPTION

MTBR - mean time between repairs (PMH)
MTTR - mean time to repair (SMH)
MV - merchantable volume per tree ($m^3$)
NA - number of activities in network
NMD - non-mechanical delay time (SMH)
NN - number of nodes in network
NP - number of least-cost paths to be selected
NSV - number of sets of standard variables
NT - number of trees per cycle
NTPH - number of trees per hectare
$OC_j$ - hourly operating costs in year "j" ($/PMH)
OE - operational effectiveness (decimal %)
OLC - oil and lubricant costs ($/PMH)
OP - operator performance factor
P - proportion of payload supported by skidder
PACKINGFT - portion of grapple area occupied by full-tree stems (decimal %)
PACKINGTL - portion of grapple area occupied by tree-length stems (decimal %)
PMH - productive machine hours
PP - purchase price ($)
Q - quantity produced per cycle
R - rolling resistance coefficient
RC - repair costs ($/PMH)
RCF - repair cost factor
SFC - specific fuel consumption (kg/kW. hr)
SHY - scheduled hours per year
SLOPE - % slope
SMH - scheduled machine hours
$SV_j$ - salvage value in year "j"
T - traction coefficient
TE - tractive effort (kg)
TW - tare weight (kg)
U - utilization (decimal %)
VPH - volume per hectare ($m^3$/ha)

| SYMBOL | | DESCRIPTION |
|---|---|---|
| W | - | operator wage ($/SMH) |
| WM | - | time spent waiting for mechanics or repair facilities (SMH) |
| WP | - | time spent waiting for repair parts (SMH) |
| WTFT | - | weight of full-trees (kg) |
| WTTL | - | weight of tree-lengths (kg) |
| $\sigma_j$ | - | duration of shortest path at node "j" |
| $\mu$ | - | fuel density (kg/litre) |

# 1. INTRODUCTION

Since the invention of the axe, increasingly sophisticated machines and systems have been developed for harvesting wood fibre from forested lands. Logging management personnel must select that combination of harvesting equipment which is best suited to the particular operating environment from the array of alternative harvesting systems which have been or could be developed[1].

The best system for any specific operating environment, whether physical, economic or social, can only be identified after all possible methods of meeting the objectives of that system have been investigated. The research discussed herein investigated the use of a computer program which selects and ranks alternative combinations of machines, facilitating the selection of equipment and the design of the least-cost forest harvesting system.

## 1.1 Research Objectives

The objectives of the research undertaken for this thesis were as follow:

a) To describe with directed networks possible alternative forest harvesting systems;

b) To compile engineering, economic and time study data on selected logging equipment;

---

[1] It is suggested that readers unfamiliar with forest harvesting terms consult a standard reference on terminology e.g. [108; 144; 145].

c) To develop production cost prediction equations for harvesting equipment;

d) To demonstrate the use of shortest path network analysis as a means of selecting optimal forest harvesting systems; and

e) To evaluate the sensitivity of the logging system to variations in its operating environment, and so determine optimum operating zones.

## 1.2 Environment Facing Canadian Loggers

Nadeau [111], Morrison [110], and others [68; 123; 142] have shown a deterioration in the competitiveness of the Canadian forest products industry compared with most other producing countries. Seventy to eighty percent of the differences in total pulp and paper manufacturing costs between Canadian and American producers has been attributed to high wood costs [142, p. 41]. Although the situation is less critical in the lumber industry, some regions of Canada have competitive disadvantages for the same reason. These high wood costs are attributable to a number of problems within the physical, economic and social environments facing Canadian loggers.

Increasing demand for forest products has resulted in greater harvests as shown in Figure 1, and forced greater utilization of what had earlier been considered stands and species of marginal value. However, Reed's [138] study of Canada's reserve timber supply concludes that the economically exploitable forests are now almost completely allocated, and only improved utilization and intensified forest management will permit further expansion of the industry.

Reduced average tree size and rapidly rising wages have prompted a trend towards the complete mechanization of forest harvesting operations as a means of raising productivity. Hand saws and horsedrawn sleighs have, for the most part, been replaced by power saws, skidders and other mechanized equipment.

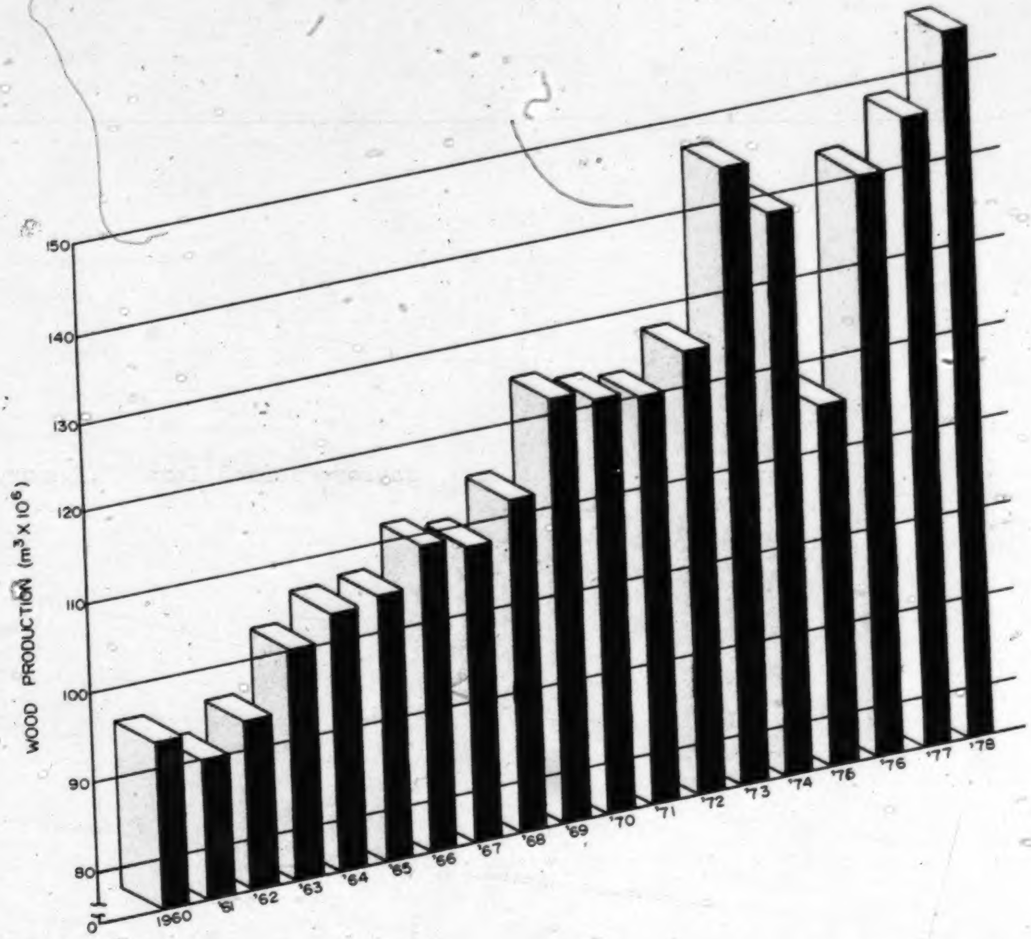


Figure 1. Total forest production in Canada 1960 – 1978 [147; 149].

The urbanization of society reduced the labour supply of an industry which had been labour intensive prior to 1960. The increased labour productivity offered by mechanization became a necessity under these circumstances. Table 1 shows that the average annual productivity of forest workers doubled in the period from 1960 to 1978.

Labour costs also increased during the period, both as a result of inflation and the need for a wage and fringe benefit package to neutralize the urbanization trend. In terms of constant value 1971 dollars[2], average wages more than doubled from $4,830 to $10,039 between 1960 and 1978.

Over the shorter term, the strong inflationary pressures following the energy crisis in 1971 produced dramatic increases in the costs of energy, lubricants and purchased supplies as Figure 2 shows.

These factors combined to produce the equivalent of a 325% increase in the total cost per cubic metre on a current dollar basis between 1960 and 1978 as shown in Figure 3. On an absolute basis, average unit costs rose at an average annual rate of over 2% during the period.

---

[2] Constant value 1971 dollars were used to remove the inflationary effects during the period. Various price indices have been applied to some cost figures as outlined in Appendix A.

Table 1. Annual Size, Productivity and Average Wage for the Labour Force Employed in Canadian Logging 1960 - 1978 [147; 149].

| YEAR | LABOUR FORCE | | PRODUCTIVITY | | AVERAGE WAGE | |
|---|---|---|---|---|---|---|
| | SIZE | % CHANGE | $M^3$/MAN | % CHANGE | 1971 $ | % CHANGE |
| 1960 | 55000 | - | 1696 | - | 4830 | - |
| 1961 | 55420 | + 0.8 | 1622 | - 4.3 | 5357 | +10.9 |
| 1962 | 55790 | + 0.7 | 1655 | + 2.6 | 5277 | - 1.5 |
| 1963 | 53921 | - 3.4 | 1849 | +11.1 | 5771 | + 9.4 |
| 1964 | 55882 | + 3.6 | 1838 | - 0.6 | 5983 | + 3.7 |
| 1965 | 53992 | - 3.4 | 1920 | + 4.5 | 6312 | + 5.5 |
| 1966 | 54317 | + 0.6 | 2002 | + 4.3 | 6686 | + 5.9 |
| 1967 | 51004 | - 6.1 | 2110 | + 5.4 | 7068 | + 5.7 |
| 1968 | 45187 | -11.4 | 2489 | +18.0 | 7434 | + 5.2 |
| 1969 | 46847 | + 3.7 | 2602 | + 4.6 | 7758 | + 4.4 |
| 1970 | 44814 | - 4.3 | 2710 | + 4.1 | 7916 | + 2.0 |
| 1971 | 40126 | -10.5 | 2982 | +10.0 | 8562 | + 8.2 |
| 1972 | 40363 | + 0.6 | 3075 | + 3.1 | 9032 | + 5.5 |
| 1973 | 49573 | +22.8 | 2900 | - 5.7 | 9177 | + 1.6 |
| 1974 | 50733 | + 2.3 | 2718 | - 6.3 | 9478 | + 3.3 |
| 1975 | 45533 | -10.2 | 2532 | - 6.9 | 9325 | - 1.6 |
| 1976 | 42185 | - 7.4 | 3298 | +30.3 | 10169 | + 9.1 |
| 1977 | 41804 | - 0.9 | 3475 | + 5.4 | 10316 | + 1.5 |
| 1978 | 45944 | + 9.5 | 3393 | - 2.4 | 10039 | - 2.7 |

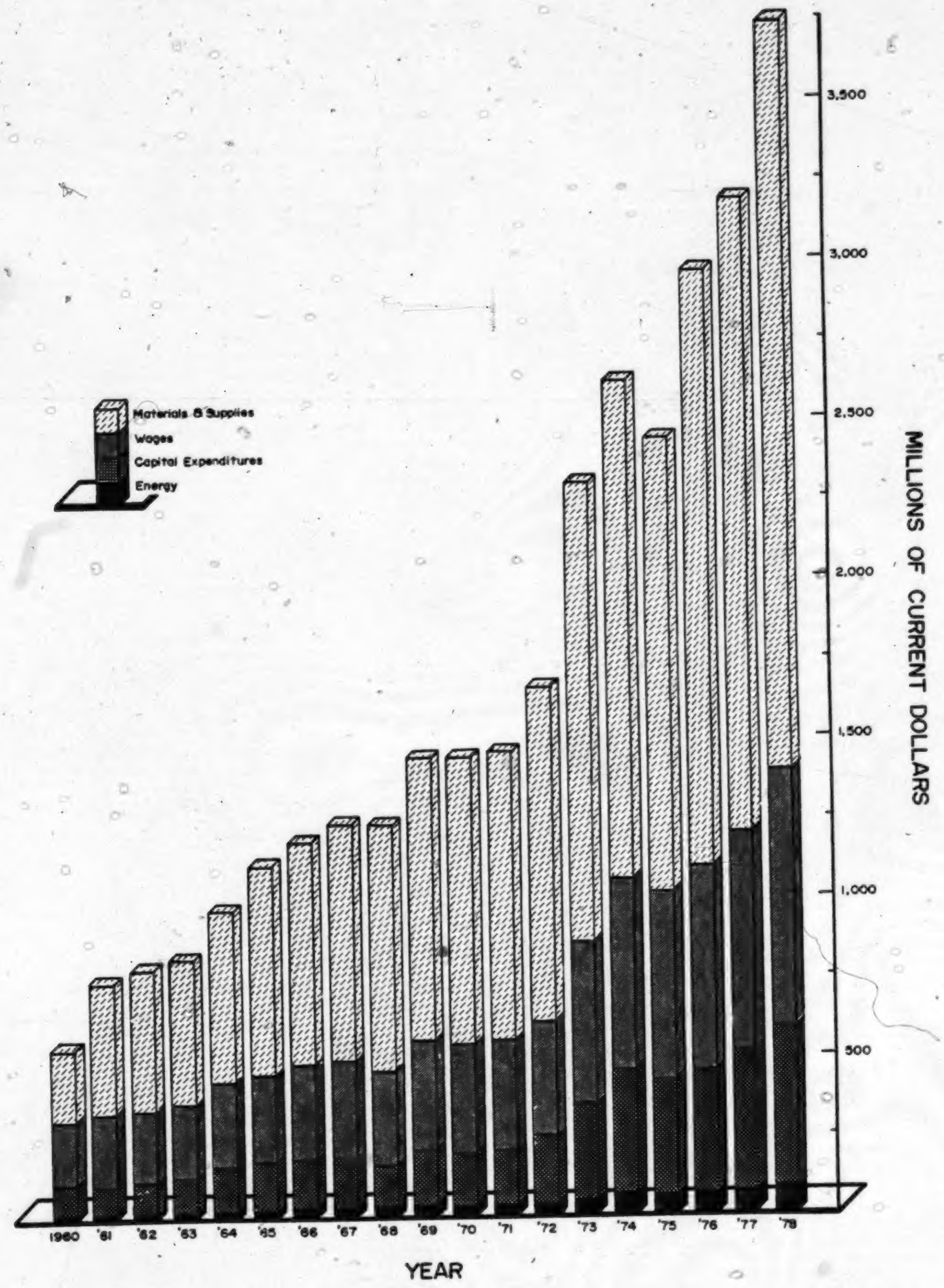


Figure 2. Breakdown of total logging costs in Canada 1960 - 1978 [147; 149; 150].

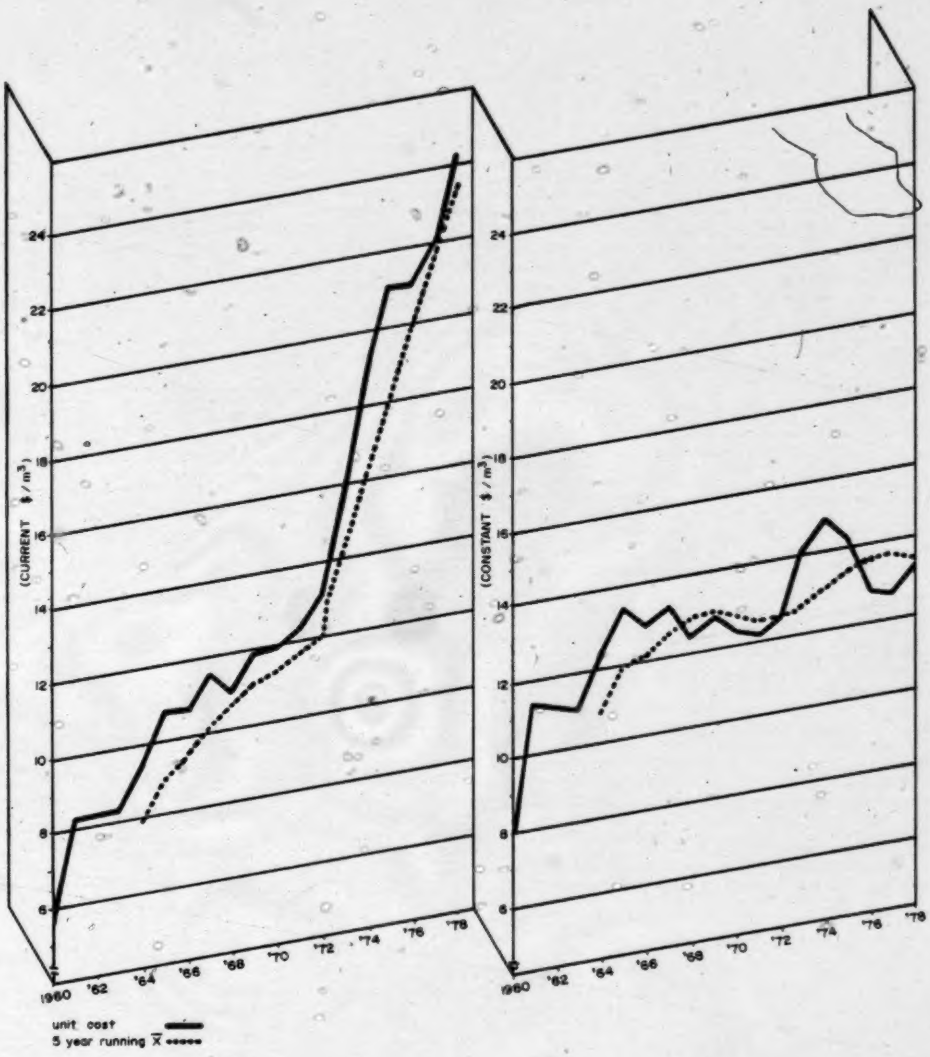


Figure 3. Unit wood costs in current and constant 1971 dollars per cubic meter in Canada 1960 - 1978 [147; 149; 150].

Although mechanization has solved some of the problems associated with labour, it has created many of its own. The complexity of logging machines has increased the necessity for the training of woodlands employees. Higher demands for skilled labour has often placed the industry in direct competition with urban employers for trained personnel. With mechanization, machine maintenance has become an increasingly important area of concern. Organizational restructuring and the development of new infra-structures became necessary to maintain and control logging machines.

Moreover, the sheer magnitude of the multi-million dollar investments in the capital assets required for large-scale harvesting operations has become a major problem. The size of the actual investment varies with the degree of mechanization and the amount of wood cut, but as Figure 4 shows, capital expenditures have risen. The ratio of capital-to-labour input costs increased by 20% in constant dollars between 1960 and 1978. This suggests that the doubling of man-year productivity shown in Table 1 is the result of a substitution of capital for labour during the period.

To measure the relative effectiveness of these production factors, a comparison of the productivity indices for capital and labour expenditures[3] is made in Table 2. During the time frame, capital productivity decreased slightly, while there was a compensating marginal increase in labour productivity.

---

[3] The productivity indices were calculated using the equation

$$\text{Index} = \frac{\text{Production}}{\text{Expenditures}} \times \frac{\text{Implicit Price Index}}{100}$$

using expenditures on capital, labour and a combination of both.

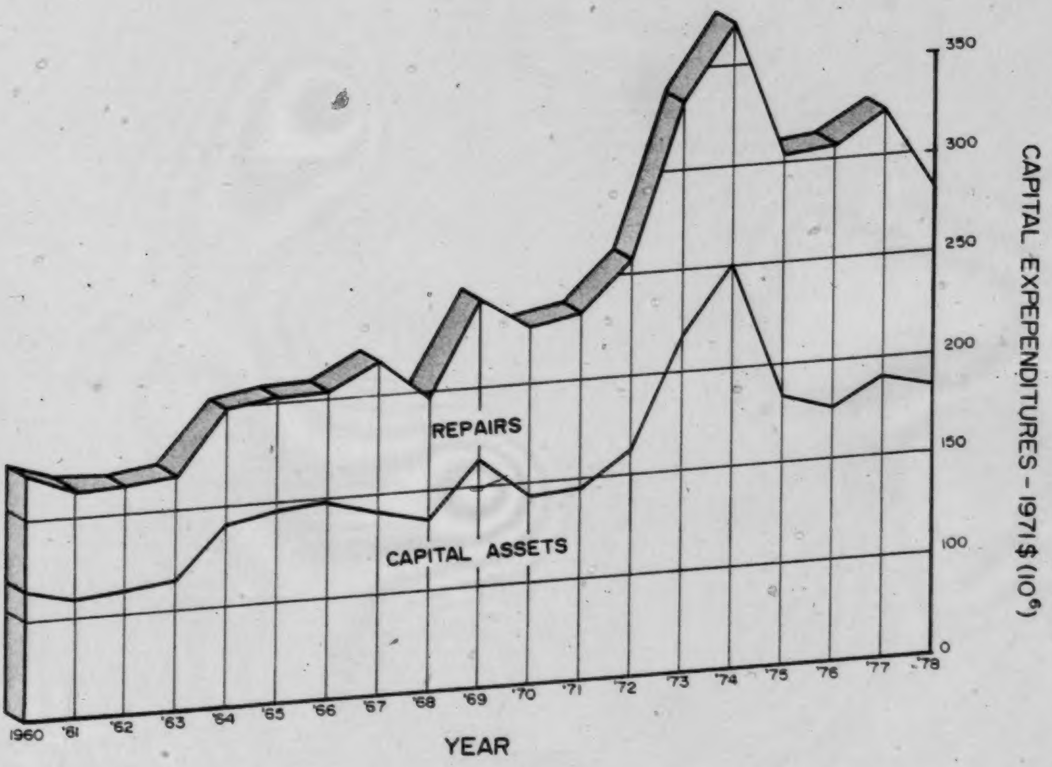


Figure 4. Total capital invested by the Canadian forest products industry in logging construction, equipment and repairs between 1960 - 1978 [150].

Table 2. Canadian Logging Productivity Indices for Capital and Labour 1960 - 1978 [147; 149].

| YEAR | CAPITAL PRODUCTIVITY | | LABOUR PRODUCTIVITY | | COMBINED PRODUCTIVITY | |
|---|---|---|---|---|---|---|
| | INDEX | PACP[1] | INDEX | PACP | INDEX | PACP |
| 1960 | 0.649 | - | 0.335 | - | 0.221 | - |
| 1961 | 0.678 | +4.5 | 0.292 | -12.8 | 0.204 | -7.7 |
| 1962 | 0.661 | +0.9 | 0.304 | -4.7 | 0.209 | -2.8 |
| 1963 | 0.704 | +2.7 | 0.310 | -2.6 | 0.215 | -0.9 |
| 1964 | 0.543 | -4.4 | 0.299 | -2.8 | 0.193 | -3.3 |
| 1965 | 0.543 | -3.5 | 0.299 | -2.2 | 0.193 | -2.7 |
| 1966 | 0.557 | -2.5 | 0.297 | -2.0 | 0.196 | -2.0 |
| 1967 | 0.592 | -1.3 | 0.296 | -1.8 | 0.197 | -1.6 |
| 1968 | 0.739 | +1.6 | 0.330 | -0.2 | 0.228 | +0.4 |
| 1969 | 0.620 | -0.5 | 0.330 | -0.2 | 0.215 | -0.3 |
| 1970 | 0.680 | +0.5 | 0.341 | +0.2 | 0.227 | +0.3 |
| 1971 | 0.680 | +0.4 | 0.341 | +0.2 | 0.227 | +0.2 |
| 1972 | 0.602 | -0.6 | 0.341 | +0.1 | 0.217 | -0.2 |
| 1973 | 0.542 | -1.4 | 0.318 | +0.4 | 0.200 | -0.8 |
| 1974 | 0.455 | -2.5 | 0.297 | -0.9 | 0.180 | -1.5 |
| 1975 | 0.476 | -2.1 | 0.292 | -0.9 | 0.181 | -1.3 |
| 1976 | 0.595 | -0.6 | 0.356 | +0.4 | 0.223 | 0.0 |
| 1977 | 0.624 | -0.2 | 0.359 | +0.4 | 0.220 | 0.0 |
| 1978 | 0.565 | -0.8 | 0.352 | +0.3 | 0.217 | -0.1 |

[1] Percent Annual Change in Productivity = PACP = $((P_t/P_o)^{1/t} - 1) \times 100$ where t is the number of years between initial period and period t, $P_o$ is the productivity index in the initial period, and $P_t$ is the productivity index in period t.

However since capital was being substituted for labour, the combination of these two factors gives a more accurate estimate of productivity. This approach indicates that a 0.1% annual decrease in the overall productivity of the Canadian logging industry occurred between 1960 and 1978. While new technologies were twice introduced into the industry during these years (skidders and harvesting equipment), they had no major impact on over-all productivity. This supports Morrison's conclusion that "neither capital nor labour were used effectively" in the transition from a labour intensive to a capital intensive industry [110, p. vi].

The net result of this stable productivity has been rises in wood costs to the point where United States producers generally enjoy a lower material costs than all Canadian production regions other than Interior British Columbia [123, p. II-26].

This has been a main contributing factor to low the profitability that threatens the availability of capital in the future. Since the threat of shortages, small tree sizes and relative inaccessibility compared to competitors will continue if not worsen in the future, one of the main problems now confronting the Canadian logging industry involves improving the productivity of capital and labour expenditures. This research investigates a method which aids woodlands management personnel in the analysis and select of systems most likely to improve productivity.

A brief outline of the basic forestry harvesting systems and their component subsystems follows.

## 1.3 Forest Harvesting Systems

Nadler's general definition of any system [112, p. 41] as the specified and organized conditions for the elements of function, inputs, outputs, sequence, environment, physical catalyst, and human agents detailed for each element in physical, rate, control, and state dimensions clearly applies to harvesting systems.

These elements relate to forest harvesting systems as follows. The function is to harvest and transport a quantity of wood fibre to some location for additional processing at minimal cost. Large quantities of trees and energy are the system's main inputs. The output of a logging operation is wood fibre at the consuming mill's site. Between the system's inputs and outputs, the operation follows a sequence of processing steps. The conditions within the forest, society and the economy are the environment in which the system operates. The physical catalysts, which aid the conversion of inputs to outputs, are the various logging machines. Woodlands workers and management are the human agents associated with the system. Thus forest harvesting operations are akin to other systems. As such, systems analysis is one method of analyzing logging systems and identifying the optimal system.

There are five distinct general categories of forest harvesting systems:

1.3.1 multiple-length,
1.3.2 tree-length,
1.3.3 full-tree,
1.3.4 whole-tree, and
1.3.5 chipwood.

Figure 5 illustrates the historical use of the different systems in Eastern Canada. Note that the basis of comparison is wood form upon delivery to roadside, rather than form upon delivery to the mill as used elsewhere in this thesis.

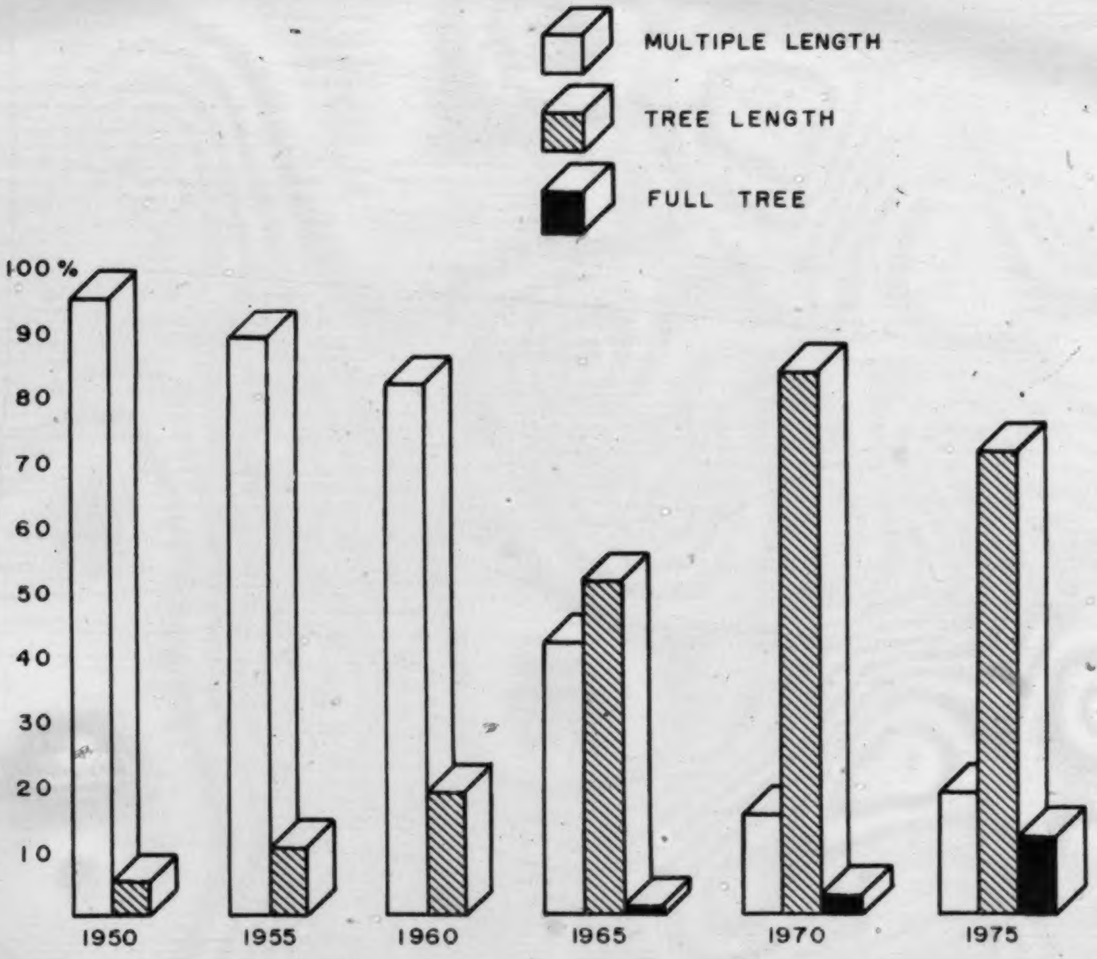


Figure 5. Historical use of different forest harvesting systems in Eastern Canada [104, p. 5].

### 1.3.1 Multiple-Length Harvesting Systems

Multiple-length harvesting systems involve the production and transport of logs of less than the merchantable height of the tree to the processing mill. Generally if the logs are over three meters in length, the system is called longwood, and if under three meters, shortwood. Both types involve the same basic operations but with some differences due to the log length. The main subsystems are as follows:

a) felling of the tree,
b) bolt preparation *i.e.* limbing, topping, and bucking,
c) transportation of wood from the stump to a central point,
d) loading,
e) transportation to the processing mill, and
f) unloading.

The sequence of the subsystems is variable, with the possibility of the transportation from stump to landing and bolt preparation subsystems being interchanged. It is also common to have bolt preparation disunited, with for example limbing and topping done at the stump, and bucking at the landing.

Historically in Canada, the multiple-length system has been the primary method of harvesting wood fibre. The ease of handling with short material when technology was less developed, the requirements of groundwood pulp mill equipment, the delivery to the mill of only "acceptable" portions of the tree, and legislated limits on the widths and lengths of truck loads were the major justifications for the continued usage of the system. Technological advances in the last 25 years have largely negated these advantages.

### 1.3.2 Tree-Length Harvesting Systems

A tree-length system produces and transports wood in logs equal in length to the merchantable height of the tree. The actual length varies with the forest environment, tree species' characteristics and the merchantability limits, but the transported logs usually exceed 12 meters in length and rarely are longer than 18 meters. This system involves the same subsystems as the multiple-length system, but the bolt preparation stage consists only of limbing and topping.

### 1.3.3 Full-Tree Harvesting Systems

Full-tree logging results in the delivery of a felled tree with the limbs largely intact to the processing plant. The bolt preparation subsystem is completely removed.

### 1.3.4 Whole-Tree Harvesting Systems

The whole or complete-tree harvesting system involves the harvesting of all wood fibre within the tree, from roots to branches. There are potential problems with nutrient cycling, soil erosion and regeneration associated with the system, so it remains largely unused in Canada. However, Keays [71; 72; 73; 74; 75] suggested that the system has great potential for some products, since the utilization of the total wood fibre produced by the tree could be increased by as much as forty percent for most Canadian species.

### 1.3.5 Chipwood Harvesting Systems

Chipwood harvesting systems deliver wood chips to the consuming mill. The chipping of trees in various forms is possible, but the inclusion of tree bark with the chips creates problems with the pulp quality with present pulping processes. The system's output are also unsuitable for utilization in lumber and veneer mills, so the potential usage of the system is limited to pulp and particle board products. The purest form of this system would be chipping of the whole-tree at the stump, and subsequently transporting wood chips to the mill.

Having described the basic forest harvesting systems, the literature covering different techniques which have been applied to the analysis of these systems will be reviewed in the next section.

## 2. LITERATURE REVIEW

In the past three decades, the trend in forest harvesting research has been away from the study of single machines to the study of groups of machines combined into systems. Prior to the mid-1960's, most studies investigated harvesting as single entities, although it was often recognized that many situations involved several activities. Since that time, the systems approach, studying problems as a collection of activities which interact, has become increasingly common.

Although many analytical techniques have been used to analyze harvesting machines and systems, the application of a particular technique has often not been limited to one use. For example, a simulation model could be developed for designing a system, and could also be used for planning and control purposes once the system existed. As such, the techniques described in the literature have been separated into their primary area of usage as follows:

2.1 Determining Machine Productivity

2.2 Planning and Controlling Logging Operations

2.3 Designing Logging Machines and Systems

2.4 Synthesis

## 2.1 Determining Machine Productivity

Most analyses of logging machines and systems used time study data, alone or in conjunction with various measurements of the operating environment, to determine machine productivity and cycle times. However, data analysis has become increasingly complex. Simple statistics such as means and standard deviations have been replaced by multiple regression and time series analysis. In recent years, operations research models using probability distributions for time elements have become common.

The main objective of most early studies was the determination of productivity and the influence of environmental factors on it. Research such as that by McCraw [100], Bennett _et al_. [8], Dibblee [35] and Harvey [63], concentrated on detailed time studies of wheeled skidders. Results of these studies indicated that about 60% of the variation in productivity could be explained by easily measured variables such as load volume and skidding distance. Several authors _e.g._ [101; 9; 27] attempted to improve the accuracy of predictions by including such factors as surface roughness, slope, brush density and ground bearing strength but with little success. Variable skidding crew motivation, changes in their physical effort (rating) in response to work conditions, and interaction between all these factors caused measurement problems.

More recent studies of skidding operations have been unable to improve the accuracy of these early prediction equations. Studies as recent as 1976 by Matthes _et al_. [98] explained about 65% of the productivity variation using a six variable multiple regression equation. In comparison, McCraw's and Hallet's studies [101] made during the 1960's, used three variables to explain 55% of the variation. Cottell et al. [27; 28] had accuracies of 80% and more using equations with two independent variables and shift-level data.

Kroger's study [77] is an exception to these relatively low accuracies. He reports coefficients of multiple determination exceeding 94%. However, his models are quite complex and their data requirements make them of questionable value for practical uses. The trade-off between accuracy and usefulness has led many researchers to avoid complex productivity prediction equations with higher accuracy since the numerical skills among those using the equations were frequently poor and problems with measuring factors such as brush density and surface roughness consistently.

In more recent years, both detailed and gross time-study procedures have been used for logging machine studies. The machine evaluation studies made by Skogsarbeten (Swedish Logging Research Foundation), the American Pulpwood Association, the Pulp and Paper Research Institute of Canada (PAPRICAN), and the Forest Engineering Research Institute of Canada (FERIC) use short-term (3 to 5 day) detailed studies to prepare productivity estimates [19; 128; 84; 46]. Other organizations around the world use similar techniques for the same purpose, e.g. [10; 12; 60].

Folkema [47] and others at FERIC have used gross time study procedures in conjuction with time recording instruments, i.e. Servis recorders, to determine long-term machine time data, productivity and causes of machine downtime.

The failure of the early researchers to quantify the unexplained variation led to the development of gross-data procedures which used shift-level or day-long periods as the basis of prediction. Productivity estimates with sufficient accuracy for production control, planning and budgeting, and in some cases greater accuracy than detailed studies, were found to be obtainable using these gross data procedures [28; 158]. Detailed time-element studies have been reserved for method studies aimed at improving work techniques, the evaluation of new machines, and for determining the probability distributions and regression equations used in simulation models.

Two conclusions are apparent from the studies chiefly concerned with determining the productivity of logging machines and systems: machine and system performance has a stochastic nature, and the interactions between system components were usually not studied.

## 2.2 Planning and Controlling Logging Operations

The results of many early time studies were intended for use in the planning and control of logging operations. Cunia [31] and Lussier [91] used statistical data gathered from time studies of equipment and crew performance to prepare production standards and control charts, and as a basis for budgeting and the evaluation of future systems.

### 2.2.1 Nomograms

Many authors have avoided the problem of low numeracy among potential users by providing nomograms for productivity and cost calculations, e.g. Ager [1], and Legault [85]. The productivity curves are usually established using regression equations developed from time studies. Costing models of various types have been used for determining operating cost of the equipment.

The so-called "Weak Link" analyzer developed by Baumgras and Martin [6] uses nomograms to aid loggers in analyzing their harvesting systems. The productivity and costing nomograms presented for the felling, skidding and transportation subsystems represent a complete systems approach. The production nomograms are limited to conditions in the Appalachian region of the United States, but the approach is adaptable.

The economic analysis of 20 logging systems used in Quebec made by Conseillers en gestion des forêts (COGEF) contains nomograms for adjusting the observed productivity of logging machines [55]. Logging chance was classed by degree of difficulty i.e. easy, medium and inexploitable, and combined with operator and task characteristics to create an adjustment factor. Although intuitively the curves appear reasonable, quantitative support is absent.

### 2.2.2 Differential Calculus

Probably the earliest application of a comprehensive mathematical analysis to the planning of timber harvesting operations was Matthew's treatment of road and landing spacing [99]. His approach used the method of equal areas to derive the average skidding distance for regularly shaped areas like circles, triangles and rectangles. The average skidding distance was used in a break-even analysis which equated variable skidding costs and road construction costs to determine optimal road and landing spacings.

Several other approaches have been developed for investigating the optimal spacing problem. Lussier [92] revised Matthew's work, recognizing the influence of terrain conditions on skidding productivity. Suddarth and Herrick [153] developed formulae based on integral calculus for the average skid distance. Their work demonstrated that Matthew's average skid distance formula for a rectangle was incorrect. Lysons and Mann [93] showd that Matthews' formula for circle wedge shapes was also in error.

All these approaches assume that the cutting block has a regular shape, two-way skidding to the landing is possible, variable skidding costs are equal from both sides, and that stand density is constant throughout the cut block. In practice, none of these assumptions is valid. Additionally, topographic features and soil conditions, such as streams, muskegs and cliffs, may prohibit positioning the landing in the central location, and increase the actual skidding operation, rather than reduce productivity.

Peters and Burke [125] extended the integral calculus approach to irregularly shaped areas, using a procedure requiring a digitizer. Peters [126] also formulated a generalized, direct solution method which uses Matthew's expression for total harvesting cost and the integral form for average skidding distance. The results showed that a necessary condition for minimum costs is that variable skidding costs equal road costs plus twice landing costs.

Donnelly [37] developed a program for a hand-held programmable calculator for calculating average skidding distance for any shape of cut-block. His method is simpler than the digitizing system of Peters and Burke, op. cit. and includes variable stand density.

Carter et al. [23] approached the optimum road layout problem using calculus on a fuller treatment of road building costs than is used in the road and landing spacing studies of the previously mentioned authors.

### 2.2.3 Mathematical Programming

In the last 15 years, operations research tools have been applied to logging problems by many researchers. Harvesting and regeneration activities were scheduled using a linear programming model by Curtis [32], but logging entered the calculations only as costs.

Donnelly [38] used linear programming to determine the optimum combination of machines subject to restraints on such factors as volume, species composition, labour supply and equipment.

Lonner [90] used linear programming to minimize storage and transportation costs for one year plans of wood transportation activities. A heuristic model is used to allocate trucks and loaders to individual landings.

More recently, Newnham [118; 119] developed a computer model for preparing annual harvesting plans. Linear programming is used to allocate constrained resources of wood and machines, so that mill demands are met throughout the year at minimum cost.

A two-part methodology for planning cable harvesting areas and assigning equipment to them was developed by Dykstra [40]. Stand, topographic and environmental restraints are combined with the mechanics of cable yarding systems to develop feasible alternatives and the harvesting costs for each block in a planning area. An integer programming algorithm is used to design optimum blocks and to allocate yarding equipment to minimize costs.

The main problems with linear programming for harvest planning are that:

a) variables are assumed to be continuous,

b) machine interactions are not considered,

c) tableaux small enough for convenient solution but large enough for accuracy are difficult to formulate, and

d) variables must be deterministic.

Various mathematical programming methods i.e. integer, and non-linear programming, can lessen the importance of the first three problems, but have not been widely used. The latter problem continues to restrict use of this technique.

### 2.2.4 Simulation

The inability of mathematical programming techiniques to describe the stochastic relationships common in harvesting operations is probably the greatest single cause of the rise simulation as the most popular operations research technique for investigating harvesting machines and systems. However, applications of these techniques have also had problems. In many studies, the scope of the system investigated was either too restricted or too general to permit proper evaluation of the total harvesting system.

For example, a simulation model presented by Gillam [61] models the movement of wood through a watershed, but does not discuss how the wood gets to the water. Other simulation models such as those by Leaf and Alexander [83], and by Bare [5], treat harvesting as only one cost variable in a comprehensive forest management model.

The complete harvesting system model was not modelled because of the nature of many harvesting operations and the overall study objectives. On many harvesting operations, the storage interval at the primary landing is sufficiently long to justify the separation of the harvesting system into subsystems without invalidating the model. In large scale models, harvesting is only one activity in the forest's growth cycle.

Corcoran's paper [26] was one of the first to describe a complete harvesting system simulation model. However, the model was prepared to illustrate the suitability of the simulation language GPSS/360, and does not appear to have been utilized for other purposes.

GASP II was used as the programming language by Johnson and Biller [11; 70] to model several alternative systems. More significant however, is that the model was validated by comparing predicted and observed results. Like most simulation models, time elements were described using statistical distributions.

Martin's Timber Harvesting and Transport Simulator differs in that regression equations in conjunction with their standard errors were used to predict cycle times [96]. No special simulation language was used.

The flexibility of all these models is limited. A more general model was developed by the American Pulpwood Association's Harvesting Research Project [152], and subsequently expanded by researchers at Virginia Polytechnical Institute and State University [120]. Six different systems can be simulated by this model in five different stands. The intent of the model was to evaluate the effects of the systems' components balances and stand conditions on overall productivity. Stand conditions were not intrinsic however, since production rates are fixed outside the model.

Bonita [13] developed a simulation model for coastal British Columbia. His model, designed for evaluating and comparing existing or potential operating policies and determining equipment requirements, was validated.

### 2.2.5 Network Analysis

Mandt [94; 95] determined the shortest route between two points in a road network using a hand calculation procedure for network analysis. Wood from different cutting areas was allocated between alternative mills by minimizing the travel time between the cutting area and the mill.

Ransing [136; 137] discussed the use of critical path analysis in the planning of a forest road construction project. Martin [97] designed a computer program for analyzing PERT networks which could be used for planning such projects.

A report by Carson and Dykstra [22] describes several computer programs for finding the shortest path through a transportation network from a landing to a destination. A programmable desktop calculator with digitizer was used to develop the network. An algorithm which finds the shortest path from any initial node to all other nodes is used to determine the best transportation route.

Applications of network analysis have been limited to areas related to planning and preparing for the actual harvest rather than analyzing alternative systems.

### 2.2.6 Production Functions

Multiple regression equations for various system components are converted to a probability density function for the complete system in a model developed by Watson and Matthes [155]. The model is based on the assumption that the system's productivity equals the minimum productivity of the components for any level of production.

### 2.2.7 Decision Trees

Woodland [157] used a decision tree as a machine costing model. He proposed that probability estimates for different events be prepared and probability weighted "expected" values be used in return on investment calculations and risk analysis. The decision to purchase a machine or system was to be made based on these expected returns.

### 2.2.8 Others

A heuristic algorithm was developed by Carlsson [21] to prepare logging plans over different planning horizons in Sweden. The short-term plans are basically cutting schedules that maximize the utilization of available machines and labour. Areas with constraints on logging activities are scheduled for cutting when the constraint's effects can be minimized, for the one-year plan. Individual areas are allocated to specific years in the 5-year plans.

Gibson and Egging [59; 41] formulated models for selecting the optimal landing location from several specified alternatives. Topographic influences on the production function and physiographical constraints are incorporated in the model. But the unit centroids used to represent the cut-blocks are inaccurate representatives, since all wood from each block is assumed to be transported from the block's geometric centre to the landing. This appears not to recognize that features which are constraining at the centre, may not apply to the complete block, thus raising average skidding distance and costs.

## 2.3 Designing Logging Machines and Systems

Several approaches have been applied to the design of logging machines and systems. Some of these approaches, particularly reliability theory, are exclusively design approaches. However, the differentiation between planning and control models, and those applied to design is imprecise, expecially with stochastic simulation models. Frequently these models can be and have been used for both purposes. Thus for the purposes of this discussion, an attempt has been made to differentiate between each model's primary objectives while recognizing the model may have other uses.

### 2.3.1 Reliability Theory

Two authors have used reliability theory to justify their approaches to logging equipment design. Kurelek's papers [78; 79] compare several multi-function machines with systems composed of single-function machines. The improved man-day productivity, lack of interdependence between machines, better materials handling characteristics, and the redundancy of some components led Kurelek to conclude that multi-function machines have inherent productivity and cost advantages over single-function machines.

On the other hand, Mellgren [105] concluded that there are no significant differences in the potential wood production costs between different machine systems. He also suggested that single-function machines are more competitive under adverse terrain conditions and in stands of large trees since machine size becomes a limiting factor.

The conflict between these authors' conclusions arises because of their treatment of machine availability. Kurelek and Mellgren generally agree on the reliability of different machine types, but Kurelek's cost calculations do not use these reliability figures. Both authors emphasize that the competence of the mechanical support organization controls whether or not an operation can be successfully mechanized.

A more recent paper by Mellgren [106] suggests that improved reliability is necessary in multi-function machines if the logging industry is to profit from their advantages. His results suggest that machines with two or three functions provide the best trade-off between the advantages of multi-function equipment and the problem of reliability as machine complexity increases.

### 2.3.2 Systems Comparison Methodologies

A methodology for analyzing logging systems was developed at Skogsarbeten in the mid-sixties [64]. The time required to complete various elements is estimated using either time study and/or design specifications, summed and converted to hourly production estimates. A more complete machine classification and expansion of this methodology was prepared by McCraw and Silversides [102] for use in North American conditions. The effects of operators on productivity through personnel delays and training, and the interference between machines are not included in these productivity estimates.

Boyd and Novak [15] used the competence of the support organization as the basis of a procedure for evaluating machine concepts and systems. Eighty-four logging systems were compared at four assumed levels of performance which reflected organizational competence. However, this approach assumed that all machines are susceptible to the same variability in performance and availability.

### 2.3.3 Simulation

Both deterministic and stochastic simulation models have been used for designing harvesting machines and systems. Levesque [86] developed a deterministic model of a logging truck based on Newtonian physics relationships to select truck components and to determine travel time estimates. Garner and Cooper [58] used a simular model based on rotational rather than distance relationships to investigate the effects of reducing the aerodynamic drag of logging trucks.

The Vehicle Mission Simulator described by Gustafson and Schneck [62] is another deterministic model used for design purposes. Vehicle speeds for specified load, soil and slope conditions are calculated for the vehicle by solving the force and moment equations [124]. The model is used to select optimum components such as power-trains and tires when designing machines.

Fiske and Fridley [44] developed a model for selecting skidding equipment based on traction characteristics. The model selects the skidder or crawler tractor which produces the lowest costs for specific terrain, load sizes and skidding distances.

Newnham [115; 116; 117] has developed several models for use in designing better harvesting machinery. The harvesting of individual trees is modelled to estimate productivity. However, the detailed stand data required for the model was not commonly available, limiting the models' potential usefulness. Terrain effects on machine behaviour were not modelled.

Other models used a combination of stochastic and deterministic relationships. Damon and Johnson [33] adapted earlier work by Almquist [3] in the modelling of logging machines. Probability distributions were used to generate the sizes and locations of trees. Time elements were calculated using deterministic relationships on such factors as boom length and extension speed. The model was used to determine the optimum specifications for a thinning machine.

Winsauer and Underwood [156] described a stochastic model for estimating the productivity of a "topwood" harvester. Unlike most of the design models, results of the simulation runs were validated and found to be in close agreement with observed results.

Several authors have attacked the problems of subsystem and system design using simulation. Routhier's stochastic model of the trucking subsystem [140] is suitable for both design and planning purposes. Garner [57] validated the model and illustrated its use with results from several applications.

Larsson [80] discussed a simulation model for analyzing alternative trucking systems for design purposes. Regression equations from time studies are used to estimate elemental times.

A simulation model for evaluating a hot logging system using shortwood harvesters and tractor-trailers was developed by Newman [113]. Results indicated that savings in delivered wood costs were possible over cold logging systems, but no validation of results was reported.

Chip harvesting systems have been simulated by Johnson and Biller [69], and by Bradley et al. [16; 17; 18]. Johnson's and Biller's SAPLOS model was developed for use in determining the best equipment mix for a chipping operation. Bradley's simulator, which was validated, was designed to estimate harvesting costs under a range of stand conditions and to determine the best equipment mix. Both models are stochastic.

### 2.3.4 Queueing Theory

Analytical methods based on the idle time distributions of machine components in series were used by Meng [107] as the basis of methodology for evaluating design changes. It is assumed that both components are operating simultaneously.

### 2.3.5 Network Analysis

An adaption of network analysis, known as line balancing was used by Corcoran [25] to determine the optimum balance of components in a harvesting system.

## 2.4 Synthesis

The literature survey indicates that many analytical techniques have been used to study foresting harvesting machines and systems. Simulation has become the most widely discussed analytical technique. However, widespread use had not followed, suggesting that simulation's primary disadvantages, model complexity and inability to determine optimal solutions directly, are restraining for potential users.

Most researchers recognized the interdependence of all harvesting activities, but subsystems have generally been modelled. Such an approach would be reasonable if the model was intended for use in controlling existing harvesting systems. However, most models were developed to assist in systems design and operations planning, tasks which demand consideration of many alternatives.

Since none of the techniques applied to date appear to have met the needs of woodlands management, trial of other techniques appear justified.

# 3. INVESTIGATIVE METHODOLOGY

The basic problem which this research considers is that theoretically every forest harvesting system operates under different physical, economic and social conditions. Thus conceivably, there could be a very large number of system designs, each of which might be optimal for some specific combination of environmental conditions.

Network diagrams which graphically represent the sequence of events involved in completing some task can be used to describe alternative methods. Various adaptations of this approach have been used to design agricultural systems, but no reference was found to its application to selecting forest harvesting systems.

Preston [134; 135] adapted the critical path method (CPM) so that both time and cost variables were evaluated simultaneously in applications to the layout and operation of piggeries and to select optimal irrigation systems. Coupland and Halyk [30] used network analysis to evaluate forage harvesting systems. A simulation model was used to select alternative paths through a network of forage handling alternatives by Lievers [87].

A computer program (SPNA) initially developed by Preston [133] for selecting the shortest path through a network, was adapted by Lievers [88] to rank all paths through the network. Ogilvie et al. [121] used SPNA to evaluate manure handling systems for swine and dairy cattle.

Safley and Price [141], and Burney et al. [20] have used different versions of the network approach to analyze alternative manure handling systems.

The shortest path network approach to system design was selected for this research because of the following advantages apparent from the literature:

a) alternative combinations and sequences of equipment can be easily outlined in network form,

b) many alternatives can be quickly and cheaply evaluated,

c) optimal and near-optimal system designs are identified for more intensive study if desired,

d) non-linear functions can be used, and

e) sensitivity analysis can be readily undertaken.

Alternative approaches such as simulation and mathematical programming do not have all these advantages.

The methodology which follows uses shortest path network analysis to assist the forest harvesting system designer identify the optimal system for his conditions. Alternative combinations of logging equipment are compared on a common basis to permit the selection of the least-cost system or systems. The procedures used will be described under the following subsections:

3.1 Preparation of the Network

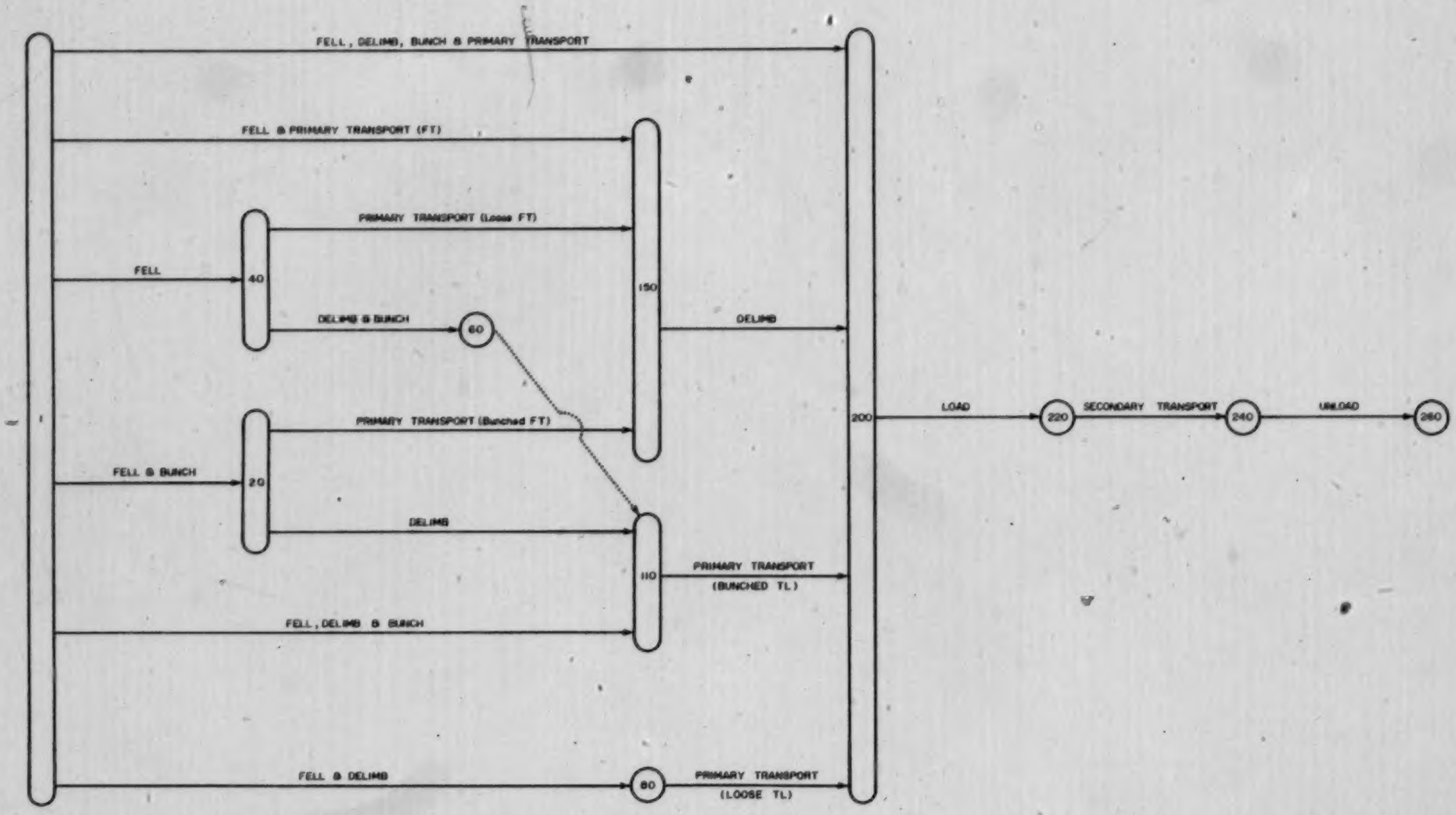
3.2 Establishment of Activity Durations

3.3 Shortest Paths Network Analysis Program

## 3.1 Preparation of the Network

A network is a graphical model which defines the sequence of events and activities between some initial state and some concluding state. An event is the identifiable point at which some defined state exists, and is denoted on a network diagram by a circle or "sausage", called a node. An activity, represented on the graph by an arrow, is an operation which is required to reach some defined state, and is called a branch, an arc or a link. An activity having no quantity associated with it but needed to maintain a logical sequence, is represented by a dashed arrow called a dummy. Dummies are also required for uniqueness and to avoid ambiguity when there are several alternative activities between two nodes. The network is the graph produced by connecting sequential events with arcs representing the activities involved in producing the change in state.

Figure 6 illustrates a generalized network diagram for alternative tree-length harvesting systems. The initial state in the tree-length system was assumed to be the tree standing in the forest. Several alternative operations and transportation activities convert from a standing tree into a tree-length log, transferring it from the stump to some intermediate landing and thence onto the processing plant. Along the way, it may or may not be temporarily stored. The unloaded tree at the mill represents the final state and node.


FELL, DELIMB, BUNCH & PRIMARY TRANSPORT
FELL & PRIMARY TRANSPORT (FT)
PRIMARY TRANSPORT (Loose FT)
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DELIMB & BUNCH
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DELIMB
PRIMARY TRANSPORT (Bunched FT)
FELL & BUNCH
20
DELIMB
110
PRIMARY TRANSPORT
(BUNCHED TL)
FELL, DELIMB & BUNCH
FELL & DELIMB
80
PRIMARY TRANSPORT
(LOOSE TL)
200
LOAD
220
SECONDARY TRANSPORT
240
UNLOAD
260

Figure 6. General network diagram of alternative activities in tree-length harvesting systems.

Because of network size and the mass of data required to describe all alternative systems, this research was limited to a tree-length harvesting system as it could be applied in Eastern Canada. As such, the "optimal" system in the remainder of this thesis is the least-cost tree-length harvesting system which might not be optimal if all alternative systems were considered. However, shortest path network analysis is a general technique and can be easily adapted for use with different networks and inputs for other systems.

Figure 7 shows an expansion of the general network diagram outlining the alternative machines and subsystems which can perform the various operation and transport activities of the tree-length system.

Three assumptions were made to reduce the network's complexity while preparing the expanded network:

a) truck transportation is the only method available for moving the wood from landing to mill. Since the mode of transportation is usually predetermined by the availability of alternatives e.g. railroads, rivers, and road systems, and most wood is trucked for some distance in Canada, this is a reasonable simplification;

b) hot-logging systems, where some equipment would off-load onto trucks are infeasible. Interference problems between machines have prohibited use of hot-logging systems in most areas; and

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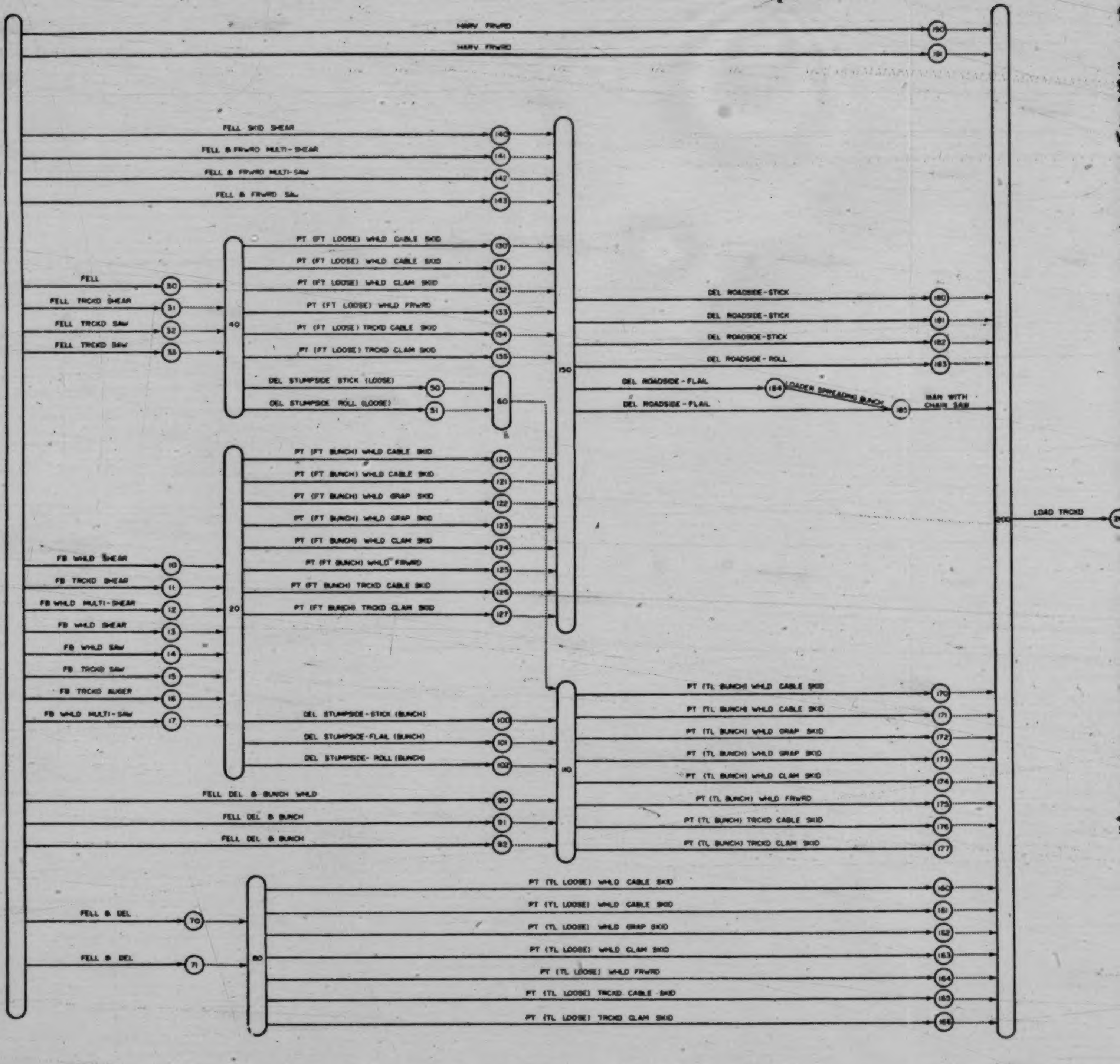
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DEL STUMPSIDE STICK (LOOSE)
50
DEL STUMPSIDE ROLL (LOOSE)
51
60
150
DEL ROADSIDE-STICK
180
DEL ROADSIDE-STICK
181
DEL ROADSIDE-STICK
182
DEL ROADSIDE-ROLL
183
DEL ROADSIDE-FLAIL
184
LOADER SPREADING BUNCH
DEL ROADSIDE-FLAIL
185
MAN WITH CHAIN SAW
200
LOAD TRCKD
PT (FT BUNCH) WHLD CABLE SKID
120
PT (FT BUNCH) WHLD CABLE SKID
121
PT (FT BUNCH) WHLD GRAP SKID
122
PT (FT BUNCH) WHLD GRAP SKID
123
PT (FT BUNCH) WHLD CLAM SKID
124
PT (FT BUNCH) WHLD FRWRD
125
PT (FT BUNCH) TRCKD CABLE SKID
126
PT (FT BUNCH) TRCKD CLAM SKID
127
FB WHLD SHEAR
10
FB TRCKD SHEAR
11
FB WHLD MULTI-SHEAR
12
FB WHLD SHEAR
13
FB WHLD SAW
14
FB TRCKD SAW
15
FB TRCKD AUGER
16
FB WHLD MULTI-SAW
17
20
DEL STUMPSIDE-STICK (BUNCH)
100
DEL STUMPSIDE-FLAIL (BUNCH)
101
DEL STUMPSIDE-ROLL (BUNCH)
102
FELL DEL & BUNCH WHLD
90
FELL DEL & BUNCH
91
FELL DEL & BUNCH
92
110
PT (TL BUNCH) WHLD CABLE SKID
170
PT (TL BUNCH) WHLD CABLE SKID
171
PT (TL BUNCH) WHLD GRAP SKID
172
PT (TL BUNCH) WHLD GRAP SKID
173
PT (TL BUNCH) WHLD CLAM SKID
174
PT (TL BUNCH) WHLD FRWRD
175
PT (TL BUNCH) TRCKD CABLE SKID
176
PT (TL BUNCH) TRCKD CLAM SKID
177
FELL & DEL
70
FELL & DEL
71
80
PT (TL LOOSE) WHLD CABLE SKID
160
PT (TL LOOSE) WHLD CABLE SKID
161
PT (TL LOOSE) WHLD GRAP SKID
162
PT (TL LOOSE) WHLD CLAM SKID
163
PT (TL LOOSE) WHLD FRWRD
164
PT (TL LOOSE) TRCKD CABLE SKID
165
PT (TL LOOSE) TRCKD CLAM SKID
166

Figure 7. Expanded network diagram of alternative tree-length harvesting systems.

2of2

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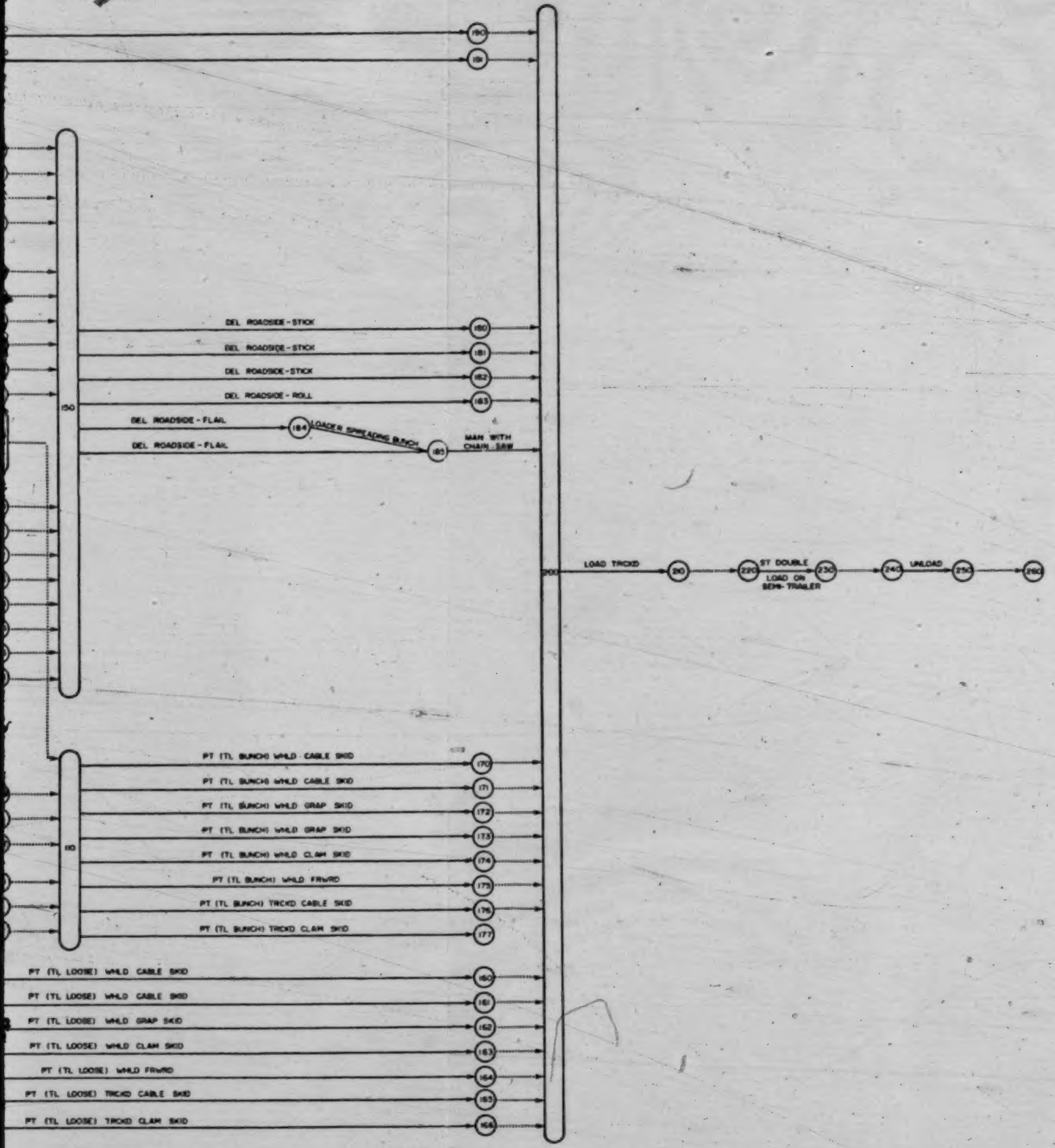
190
191
150
DEL ROADSIDE - STICK
180
DEL ROADSIDE - STICK
181
DEL ROADSIDE - STICK
182
DEL ROADSIDE - ROLL
183
DEL ROADSIDE - FLAIL
184
LOADER SPREADING BUNCH
DEL ROADSIDE - FLAIL
185
MAN WITH CHAIN SAW
200
LOAD TRCKD
210
220
ST DOUBLE
LOAD ON SEMI-TRAILER
230
240
UNLOAD
250
260
110
PT (TL BUNCH) WHLD CABLE SKID
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PT (TL BUNCH) WHLD CABLE SKID
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PT (TL BUNCH) WHLD GRAP SKID
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PT (TL BUNCH) WHLD FRWRD
175
PT (TL BUNCH) TRCKD CABLE SKID
176
PT (TL BUNCH) TRCKD CLAM SKID
177
PT (TL LOOSE) WHLD CABLE SKID
160
PT (TL LOOSE) WHLD CABLE SKID
161
PT (TL LOOSE) WHLD GRAP SKID
162
PT (TL LOOSE) WHLD CLAM SKID
163
PT (TL LOOSE) WHLD FRWRD
164
PT (TL LOOSE) TRCKD CABLE SKID
165
PT (TL LOOSE) TRCKD CLAM SKID
166

ernative tree-length harvesting systems.

c) temporary storage activities usually have durations less than a week so that no interest charges are added to production costs in lieu of the capital tied-up in uncompleted products. Lengthy storage between activities is common only between the harvesting and transportation subsystems. This delay varies from a few days to as much as a year depending on the specific operation. All systems are likely to have a delay of similar duration at this point.

## 3.2 Establishment of Activity Durations

Each arc in the network diagram of the alternative systems shown in Figure 7 was assigned a duration. In this analysis, activity durations were measured as wood cost (CW) expressed as a cost per cubic metre of wood produced.

The general relationship for the duration of any activity reflects the economics and productivity of the machinery and labour involved in the activity.

$$CW = \frac{HCOST}{HPROD} \qquad (1)$$

where: CW = wood cost for the activity ($\$/m^3$)

HCOST = hourly costs for the machinery and labour used in the activity (\$/productive machine hour)

HPROD = hourly productivity of the machinery and labour used in the activity ($m^3$/productive machine hour).

The derivation of the equations used to estimate the hourly costs and productivity for the activities are discussed in the next two sections. The duration of each activity measured in dollars per cubic metre of wood produced were calculated using equation 1 from the estimates of hourly costs and productivity.

### 3.2.1 Cost Prediction Equations

A costing method based on optimal economic machine life was used to predict equipment costs on a before-tax basis. This approach was selected because the tendency for maintenance costs to increase and for productivity to decrease as a machine ages, results in an economic life that is often shorter than the physical life.

The prediction of logging equipment costs considered the following items:

a) purchase price,
b) machine life,
c) salvage value,
d) cost of capital (interest rate),
e) insurance costs,
f) licensing costs,
g) labour costs,
h) fuel, lubricant and hydraulic oil costs,
i) maintenance costs, and
j) machine utilization.

Costing models used previously in studies of logging machines and systems have faults related to their treatment of capital costs. The straight write-off approach used by Boyd and Novak [15] makes no charge for invested capital and assumes no salvage value. The method used in PAPRICAN's and FERIC's machine evaluation studies e.g. [128; 85], write-off plus interest on half the investment, assumes no salvage value and equal annual interest charges. The widely used straight-line write-off plus interest on the average investment e.g. [6; 24; 154] fails to recognize compound interest effects. All these methods assume an equal annual write-off fixed by an estimate of recovery period which is usually defined as the machine's "useful" life.

This research used a capital recovery with return approach to calculate capital costs. In comparison, the straight-line write-off plus interest on the average investment, the most accurate of the previously discussed costing methods, provides capital cost estimates which are about 11% low for a 10 year recovery period and a 12% interest rate. The capital costs (CC) expressed in annual equivalent dollars per productive machine hour (PMH) were calculated using the formula

$$CC_j = \frac{(PP-SV_j)\ CRF + SV_j \times I}{SHY \times U} \qquad (2)$$

where: $CC_j$ = capital costs in year "j" (\$/PMH)

PP = purchase price (\$)

$SV_j$ = salvage value in year "j"

CRF = capital-recovery factor = $\frac{I(1 + I)^j}{(1 + I)^j-1}$

I = interest rate (decimal %)

SHY = scheduled hours yearly (scheduled machine hours)

U = utilization (decimal %).

A machine's salvage value is a measure of the remaining utility in the machine. Value is lost over time as the efficiency of the machine decreases. For example, an engine reaches its maximum efficiency following a short run-in period after which its overall efficiency declines as the cylinder walls, pistons and rings wear. The machine always maintains some value if only as scrap metal though the costs of disposal may negate any salvage value.

For this analysis, a machine's value was assumed to decrease at an annual rate of 30%. The salvage value of a machine in year "j" ($SV_j$) was estimated to be

$$SV_j = PP\ (1 - 0.30)^j \qquad (3)$$

The remaining costs of harvesting equipment consists of both fixed and variable cost items. Licensing, insurance and to a lesser extent operator wages are fixed and are incurred whether or not the machine operates. The variable costs of fuel, oils and lubricants, and repairs are dependent on the number of hours worked by the machine. All these costs were converted to a productive machine hour basis.

Insurance costs (INC), an expenditure for protection against damage to the machine, were assumed to be a constant 3% of the machine's residual value annually.

$$INC = \frac{0.03 \times SV_j}{SHY \times U} \qquad (4)$$

Licencing costs (LC) were included only for the truck and trailer in this analysis. This cost was fixed at $1700 per annum based on the vehicle registration fees of the province of Ontario. Other equipment would not usually be licensed for highway travel.

$$LC = \frac{\$1700}{SHY \times U} \qquad (5)$$

Both operator wages and fringe benefits based on a recent union contract [4] were included in manpower costs (MC). A fringe benefit factor (FBF) equalling 35% of direct wages was applied. It was assumed that manpower costs would continue to rise at an average rate of 5% annually in constant dollars as they have in the past twenty years. Hourly manpower costs ($/PMH) were calculated using the equation

$$MC = \frac{W\ (1 + FBF) \times (1.05)^{j-1}}{U} \qquad (6)$$

where: W = operator's wage ($/scheduled machine hour).

The cost of fuel (FC) is dependent on engine design characteristics, speed and efficiency, fuel density, fuel price and the load factor (LF). The load factor, a measure of the severity of the job and conditions under which the machine is operating, is defined as the actual fuel consumption as a proportion of the maximum capacity of the engine to burn fuel. Sample load factors typical of harvesting equipment are summarized in Table 3. Hourly fuel costs ($/PMH) were estimated using the following equation.

$$FC = 0.21 \times GP \times LF \times FP \qquad (7)$$

where: GP = gross engine power (kW)

FP = fuel price ($/litre).

It was assumed that fuel consumption occurs only when the machine is producing wood. In reality, some non-productive operating time does occur, but it usually represents less than 3% of scheduled time. As such, its effect on costs is insignificant and affects all machines approximately equally.

Table 3. Sample Load, Hydraulic Complexity and Repair Cost Factors for Various Logging Machines [24; 154].

| EQUIPMENT TYPE | LOAD FACTOR | HYDRAULIC COMPLEXITY FACTOR | REPAIR COST FACTOR |
|---|---|---|---|
| Skidder | 0.65 | 0.15 | 0.08 |
| Forwarder | 0.70 | 0.40 | 0.08 |
| Tracked Feller | 0.65 | 0.25 | 0.10 |
| Feller-Bunches | 0.65 | 0.25 | 0.11 |
| Feller-Forwarder | 0.70 | 0.40 | 0.10 |
| Tree-Length Harvester | 0.65 | 0.40 | 0.12 |
| Stripper Delimber | 0.70 | 0.40 | 0.10 |
| Flail | 0.70 | 0.25 | 0.11 |
| Knuckleboom Loader | 0.70 | 0.25 | 0.08 |
| Tractor-Trailer | 0.75 | 0.15 | 0.13 |

The cost of oil and lubricants (OLC) varies with engine power and the capacity and complexity of the hydraulic system. These costs are commonly expressed as a proportion of fuel costs since a strong relationship exists between the unit prices of fuel, oils and lubricants.

$$OLC = FC \times HCF \tag{8}$$

where: HCF = hydraulic complexity factor (see Table 3).

The average hourly repair costs (RC) over a machine's life were estimated using the following equation [24, p. 28-29; 15, p. 5].

$$RC = \frac{PP \times RCF}{1000} \tag{9}$$

where: RCF = repair cost factor ($/$1000 of purchase price/PMH). This cost includes all parts and mechanics' labour. The repair cost factor depends on machine type, operating conditions and the competence of the maintenance organization. Typical values for this factor are shown in Table 3.

A constant repair cost factor was used because long-term patterns of repair costs for logging equipment tend to be constant after adjustment for inflation until the frame fails. Boyd suggests that the reduced repair time with age results from corrective action on problem areas and the build-up of maintenance experience [14, p. 17]. In addition, much of the machine is not as old as the chassis since components are continually replaced during repairs.

Total hourly operating costs (OC) are calculated by summing insurance, licensing, manpower, fuel, oil and lubricant and repair costs.

$$OC = INC + LC + MC + FC + OLC + RC \tag{10}$$

Utilization, that is the proportion of scheduled hours that the machine is actually productive, is dependent upon the mechanical reliability inherent within the machine, and the operational effectiveness of the woodlands organization.

One measure of a machine's mechanical reliability is its availability, that is the portion of total scheduled time in which the machine's mechanical condition permits work. The availability (A) of a machine can be defined as

$$A = \frac{MTBR}{MTBR + MTTR} \qquad (11)$$

where: MTBR = mean time between repairs

MTTR = mean time to repair.

Values used in this research for the MTBR of logging equipment were gathered from various long-term studies of machine repair statistics e.g. [51; 65; 132]. Where values were unavailable, estimates were made by combining available information for similar components on other equipment [78; 106].

A mean time to repair (MTTR) of 1.8 hours was assumed in determining the mechanical availability [14, p. 17]. The MTTR varies with machine and mechanical characteristics such as accessibility and part complexity, the mechanic's skill and the facilities with which he works, but the 1.8 hour value is typical of most harvesting machines and woodlands maintenance organizations.

Availability is not directly convertible to utilization, since some repairs may be completed outside scheduled hours. Some companies' maintenance policies restrict repairs to scheduled hours, but in many cases 85% of all repair time occurs within scheduled hours [48, p. 4; 49, p. 4].

In addition servicing activities such as fuelling, cleaning, oil changes and preventive maintenance, are required on the machine. The time required for these activities varies with the manufacturer's recommended servicing schedule and on company policy, but is proportional to the machine's productive hours. Typically, 10% of productive hours are spent servicing the machine. Availability thus becomes

$$A = \frac{MTBR}{1.1 \times MTBR + 0.85 \times MTTR} \qquad (12)$$

Operational effectiveness (OE) is the other factor which affects the machine utilization. This factor measures the organizational and human controlled performance of the machine.

$$OE = \frac{PMH}{PMH + WM + WP + NMD} \qquad (13)$$

where: WM = time spent waiting for mechanic(s) or repair facilities,

WP = time spent waiting for repair parts,

NMD = non-mechanical time delay.

Boyd [14, pp. 50-51] suggested that non-mechanical delay time could be divided into:

a) Operational lost time, caused by weather or terrain conditions (*e.g.* warm-up or machine stuck), interference between other machines in the system, waiting for supervisor's instructions, aiding other machines, *etc.*;

b) Personal (*e.g.* operator late, sick, rest allowances); and

c) In-shift moving (*e.g.* moving between cut blocks).

Various studies of operational effectiveness have shown it to be extremely variable ranging from 54% [14, p. 26] to 95% [65, p. 4]. Values of operational efficiency appropriate to each machine were used in the analysis.

The product of availability and operational effectiveness is utilization (U).

$$U = A \times OE$$

$$= \frac{MTBR}{1.1 \times MTBR + 0.85 \times MTTR} \times OE \qquad (14)$$

The utilization factor was used to convert costs from a scheduled hour to a productive hour basis where necessary.

The sum of the capital and operating costs are the total machine costs. However, since both vary with machine age, the cash flows were converted to a common time basis. The operating costs for each year are discounted and summed, and the total converted to annual equivalent dollars per productive machine hour.

$$EAC_j = CC_j + CRF \times \left( \sum_{k=1}^{j} OC_k \times (1+i)^{-k} \right) \qquad (15)$$

where: $EAC_j$ = equivalent annual cost in year "j" ($/PMH)
$OC_k$ = operating costs in year "k" ($/PMH)

Hourly operating costs were measured in constant dollars, so an "inflation-free" interest rate of 12% was used in the analysis.

The machine age which produced the minimum equivalent periodic cost for equation 15 is the optimum economic life [43, pp. 125-147; 139, pp. 90-214]. It was assumed that obsolescence due to technological changes necessitate machine replacement within a maximum of 10 years. If the lowest cost point had not been reached by that point, the optimum life was assumed to be 10 years. The machine hourly cost (HCOST) used to calculate activity durations (equation 1) was the equivalent periodic cost for the machine kept for its optimal life.

$$\text{HCOST} = \text{Minimum}_{j=1\to10}\,(\text{EAC}_j) \qquad (16)$$

### 3.2.2 Productivity Prediction Equations

The productivity of forest harvesting equipment is dependent on a basic cycle time inherent to the machine which is modified by conditions in the physical environment and by operator performance. As such, a model of productivity is

$$\text{HPROD} = \frac{Q \times 6000}{CT\ (1 + EF + OP)} \tag{17}$$

where: HPROD = hourly productivity ($m^3$/PMH)

Q = quantity produced per cycle ($m^3$)

CT = machine cycle time (centiminutes per cycle)

EF = productivity adjustment factor for physical environmental conditions

OP = productivity adjustment factor for operator performance.

However, the potential usefulness of this model is limited.

Machine design itself fixes the potential zone of application for a piece of harvesting equipment. For example, a feller-buncher can operate only where the slope is less than some critical angle above which the machine will roll over. Similarly a skidder can pull a larger load only while its tractive effort exceeds the forces resisting skidding. Since performance decreases rapidly as these physical limits are reached, machines tend to be used in areas where performance is least affected by physical conditions. Within each zone of application, tree parameters such as stem volume are frequently the only influencing factor.

As previously discussed, quantifying environmental influences has proved to be extremely difficult because of interactions between various conditions, and the variability of the micro-environment. Equipment such as trucks and loaders which operate under relatively constant conditions are the only consistent exception.

Quantifying factors affecting operator performance has proved equally difficult. While many authors e.g. [85] have observed operator effects on cycle times, these differences could frequently be attributed to inexperienced operators. The study of tractor-mounted shears by Cottell et al. [29] was the only study found during the literature review which quantified the impact of factors such as experience, motivation and manual dexterity on operator performance.

The best available predictive equations for machine cycle time have coefficients of multiple determination ($R^2$) which explain less than 65% of cycle time variation. Frequently only a small portion of the cycle time was variable, with machine design and unmeasured or unused variables producing large constants in the equations. While recognizing the problems involved, this research used the available information on cycle times taken in most cases from various machine evaluation studies.

As such, a simpler model of productivity was used

$$HPROD = \frac{MV \times 6000}{CT} \qquad (18)$$

where: MV = merchantable volume per tree ($m^3$).

The equations for machine cycle time (CT) used in this analysis are summarized in Appendix B. The hourly productivity (HPROD) of each activity was calculated using equation 18.

Since the productivity and most cycle time calculations required various tree parameters, relationships for stump diameter, merchantable tree-length, green weights of tree-lenths and full-trees, and merchantable volume were identified based on tree diameter breast height (DBH). These equations are summarized in Appendix B.2 for the four main softwood species in Eastern Canada.

### 3.2.3 Example of Activity Duration Calculations

To illustrate how the hourly cost and productivity estimates were related, the activity duration calculation for the arc joining nodes 1 and 142 in Figure 7 follows.

The machine used in this activity is a Koehring KFF feller forwarder. Table 4 summarizes the costing data used in the sample calculation. The general variables apply to all activities. Activity variables are specific to the machine used in the activity.

By substituting the costing variables in Table 4 into equations 2-14, the hourly operating and capital costs shown in Table 5 were calculated. Since the operating costs are a future value, they were converted to an annual equivalent before summation with capital costs to obtain total hourly costs (equation 15).

Table 4. Costing Variables for the Sample Activity Duration Calculation.

General Variables:

| | |
|---|---|
| Interest Rate (%) | 12 |
| Fuel Price ($/litre) | 0.22 |
| Repair Time In-Shift (% of total repair time) | 85 |
| Fringe Benefit Factor (% of hourly wage) | 35 |
| Insurance Rate Factor (% of unrecovered value) | 3 |
| Rate of Lost Utility (% per year) | 30 |

Activity Variables:

| | |
|---|---|
| Scheduled Hours Yearly (SMH) | 3840 |
| Purchase Price ($) | 325 000 |
| Hourly Wage ($/SMH) | 9.66 |
| Gross Power (kW) | 257 |
| Load Factor | 0.70 |
| Hydraulic Complexity Factor | 0.25 |
| Repair Cost Factor | 0.10 |
| Mean Time Between Repairs (PMH) | 11.8 |
| Operational Effectiveness | 0.90 |
| License Cost ($/yr) | 0 |

Table 5. Equivalent Annual Hourly Cost ($/PMH) for the Sample Calculation.

| END OF YEAR NUMBER | HOURLY OPERATING COSTS | PRESENT WORTH FACTOR | PRESENT WORTH OF HOURLY OPERATING COSTS (BxC) | SUM OF PRESENT WORTH OF HOURLY OPERATING COSTS (ΣD) | CAPITAL RECOVERY FACTOR | EQUIVALENT ANNUAL HOURLY OPERATING COSTS (ExF) | EQUIVALENT ANNUAL HOURLY CAPITAL COST | TOTAL EQUIVALENT ANNUAL HOURLY COST (G+H) |
|---|---|---|---|---|---|---|---|---|
| A | B | C | D | E | F | G | H | I |
| 1 | 63.14 | 0.8929 | 56.38 | 56.38 | 1.1200 | 63.14 | 48.56 | 117.70 |
| 2 | 63.30 | 0.7972 | 50.46 | 106.84 | 0.5917 | 63.22 | 41.69 | 104.91 |
| 3 | 63.72 | 0.7118 | 45.36 | 152.20 | 0.4164 | 63.37 | 36.39 | 99.76 |
| 4 | 64.34 | 0.6355 | 40.89 | 193.08 | 0.3292 | 63.56 | 32.26 | 95.82 |
| 5 | 65.12 | 0.5674 | 36.95 | 230.03 | 0.2774 | 63.81 | 29.01 | 92.82 |
| 6 | 66.04 | 0.5066 | 33.46 | 263.49 | 0.2432 | 64.08 | 26.44 | 90.52 |
| 7 | 67.05 | 0.4524 | 30.33 | 293.82 | 0.2191 | 64.38 | 24.39 | 88.77 |
| 8 | 68.16 | 0.4039 | 27.53 | 321.35 | 0.2013 | 64.69 | 22.73 | 87.42 |
| 9 | 69.35 | 0.3606 | 25.01 | 346.36 | 0.1877 | 65.01 | 21.39 | 86.40 |
| 10 | 70.63 | 0.3220 | 22.74 | 369.10 | 0.1770 | 65.33 | 20.28 | 85.61 |

In the example, a minimum cost point was not reached within a 10 year period. Thus, the hourly cost (HCOST) of the activity was equated to the equivalent hourly cost in year 10, $85.61 per productive machine hour.

Table 6 summarizes the operating variables used to calculate hourly productivity. The values for the weight of full trees and merchantable volume per tree were calculated for average tree size using the tree parameter equations in Appendix B.2 for black spruce.

Table 6. Productivity Variables for the Sample Activity Duration Calculation.

| | |
|---|---|
| Operating Variables: | |
| Species | Black Spruce |
| Average Tree Size (DBH in cm) | 18.00 |
| Average Primary Transport Distance (meters) | 200 |
| Calculated Variables: | |
| Weight of Full Tree (kg) | 195.6 |
| Merchantable Volume per Tree ($m^3$) | 0.152 |

The cycle time per tree (CT) for the Koehring KFF was calculated using the equation [85, p. 5]

$$CT = 49.4 + \frac{(52 + 5.84 \times DIST)}{NT} \tag{19}$$

$$- \ 7.2 \times (INT\ (\frac{1135}{3 \times WTFT}) + 1)$$

$$= 42.4 \times MV$$

$$= 52.76 \text{ cmin/tree}$$

where: DIST = one-way travel distance (200 x 1.4 = 280 m)

NT = number of trees per trip = INT $(\frac{29000}{WTFT})$ = 148

INT = integer function which returns the non-decimal portion of a number

WTFT = weight of full trees (kg)

MV = merchantable volume per tree ($m^3$).

Substituting the cycle time into equation 18 gives the hourly productivity.

$$HPROD = \frac{MV \times 6000}{CT}$$

$$= \frac{0.152 \times 6000}{52.76}$$

$$= 17.3 \ m^3/PMH$$

Combining the hourly cost and productivity estimates in equation 1 gives the activity's duration.

$$CW = \frac{HCOST}{HPROD}$$

$$= \frac{85.61}{17.3}$$

$$= \$4.96/m^3$$

## 3.3 Shortest Path Network Analysis Program

An interactive package of BASIC computer programs entitled LOGNAP, an acronym for LOGing Network Analysis Programs, was developed to analyze a network of alternative systems such as that developed in Section 3.1. The programs define the network, calculate the activity durations and rank a user-specified number of least-cost paths through the network.

The flowchart shown in Figure 8 summarizes the basic logic sequence of LOGNAP. The complete program listing and some explanation of the non-standard features in the particular BASIC interpreter used in the research are contained in Appendix C.

The sections which follow discuss the limitations on the size of network to be analyzed, and algorithms used to renumber nodes and find the shortest paths.

### 3.3.1 Program Limitations

Five basic parameters are entered to describe the network and control processing:

a) the number of activities in the network,

b) the number of nodes in the network,

c) the number of least-cost paths desired by the user,

d) an estimate of the maximum number of nodes on any least-cost path, and

e) the number of sets of variables.

As presently dimensioned, the number of activities and nodes in the network is limited to 250, a maximum of 50 paths can be selected, and a path cannot contain more than 25 nodes.

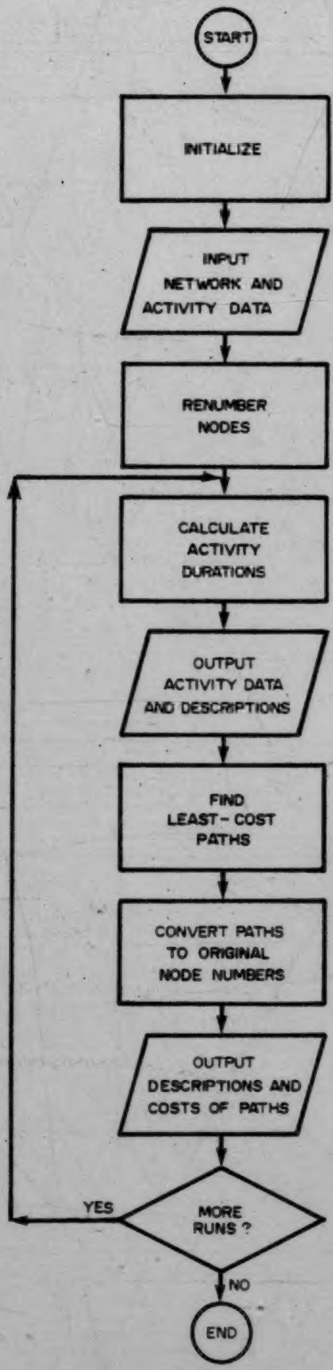
START
INITIALIZE
INPUT NETWORK AND ACTIVITY DATA
RENUMBER NODES
CALCULATE ACTIVITY DURATIONS
OUTPUT ACTIVITY DATA AND DESCRIPTIONS
FIND LEAST-COST PATHS
CONVERT PATHS TO ORIGINAL NODE NUMBERS
OUTPUT DESCRIPTIONS AND COSTS OF PATHS
MORE RUNS ?
YES
NO
END

Figure 8. Flowchart outlining the logic sequence of LOGNAP.

### 3.3.2 Node Renumbering Routine

The subroutine RNUM renumbers the network nodes to satisfy the so-called I-J rule[4]. This was included in LOGNAP to:

a) simplify the network development process by permitting haphazardly numbered nodes to be used,

b) facilitate modification of the network as required, and

c) satisfy the requirements of the shortest path algorithm.

The routine was one adapted by Burney [20] from one developed earlier by Lievers [88].

The nodes of the network are numbered between 1 for the origin, that is the node having no predecessors, and the total number of nodes in the network for the terminus using all numbers between these values.

The following are the main steps in the routine:

STEP (a) - identify the terminal node number of the network, and set counters.

STEP (b) - increment activity counter, and test if all activities have been checked. If so, transfer to Step (g).

STEP (c) - identify an activity having the terminal node, and equate the terminal node of the activity to the highest remaining terminal node number. Note that during the initial pass, the highest remaining terminal node number is the number of nodes in the network.

---

[4] The I-J rule requires that the nodes in a network be numbered so that the initial node number of any activity is less than the terminal node of that activity.

STEP (d) - test if the other activities have the same initial node. A unique initial node implies that no alternative path exists between the initial and terminal nodes of the activity. If the node is not unique, transfer to Step (b).

STEP (e) - decrement the highest remaining initial node number, and set the initial nodes of all activities having that initial node to the highest remaining node number.

STEP (f) - if all initial nodes have been renumbered, go to Step (h). If not, transfer to Step (b).

STEP (g) - decrement the highest remaining terminal node number, and identify the initial node of the highest remaining uprenumbered activity. Reset activity counter and transfer to Step (b).

STEP (h) - reset the initial nodes to their original values, and establish a key for the renumbered nodes.

## 3.3 Yen's Algorithm

The shortest paths through the network are determined using an algorithm developed by Yen [159]. This algorithm increases its computational needs linearly with relation to the number of paths sought, whereas other approaches to the shortest path problem, e.g. Lievers [88] increase their computational requirements exponentially.

Yen's algorithm capitalizes on the fact that once the shortest path has been found, the nodes on any sub-optimal path must coincide with at least one node on the previously identified paths. Thus to find the next shortest path, only the shortest deviations from the previously found paths need to be evaluated. The shortest of these candidates is the next best path.

As proposed by Yen, two lists (matrices) are used to store the best paths found so far and the candidate paths respectively. In LOGNAP a modification which reduces the storage requirements has been made to the algorithm. Since only the desired number of paths need to be stored, both lists can be saved in the same matrix. The best paths are stored in the top portion of the matrix and the candidates in the bottom part. As each path is identified, it is inserted in the matrix at the appropriate position from lowest to highest cost and any longer paths are forced down in the stack or even dropped. Upon completion of each iteration, the shortest candidate path is added to the bottom of the permanent list by incrementing a row counter by one.

The basic steps in the algorithm are as follows:

STEP (a) - find the shortest path through the network. In LOGNAP the shortest path between any two nodes was found using Elmaghraby's algorithm (see next section).

STEP (b) - for each subsequent path desired, check if the subpath between each node of the most recently found path and the origin node coincide with a portion of any previously found paths. If so, set the duration of the activity following the match to a large number.

STEP (c) - find the shortest path around the blockage to the terminal node. This subpath becomes the spur.

STEP (d) - form a new path by joining the portion of the path behind the blockage, the root, with the spur and add the path to the list of candidates.

STEP (e) - select the shortest path from the list of candidates and add to the permanent list.

STEP (f) - continue at Step (b) until the number of desired paths has been found.

Satisfaction of the I-J rule is necessary for Yen's algorithm. Before the paths are outputted, the original nodes are restored using the key developed in the node renumbering routine.

The formulation of Yen's algorithm used in LOGNAP is based on a program GSPNA developed by Horne [67]. Although GSPNA is less efficient than a second program GMSP also prepared by Horne, storage limitations made it preferable on the computer used in this research. The more efficient GMSP version of the algorithm can be easily adapted for use in LOGNAP if run on a larger computer (>64K of core memory).

### 3.3.4 Elmaghraby's Algorithm

Numerous algorithms have been developed for finding the shortest path between two specified nodes, e.g. Bellman and Kalaba [7], Dantzig [34], Dijkstra [36], Ford and Fulkerson [54], and Minty [109]. A 1969 review of shortest path algorithms made by Dreyfus [39] concluded that the Dijkstra algorithm was the most efficient at that time. Other shortest path routines have been developed since 1969, e.g. Yen [160] and O'Regan [122], but while efficient, they are not general. Moreover these algorithms are concerned with the shortest path through a directed, cyclic network.

The network developed for this research is directed but contains no loops. The above-mentioned algorithms could be used in this application, but an easier approach exists since the network can be numbered to satisfy the I-J rule. Since only those activities whose initial node equals or exceeds the origin node of the path need to be evaluated, half the number of additions and comparisons is required in an acyclic network compared to a cyclic.

By identifying the optimal predecessor node, the initial node producing the lowest duration, the optimal path can be found by working backwards through the network.

Elmaghraby [42, p. 10] proposed a dynamic programming algorithm for the shortest path through a directed, acyclic network which uses the following relationship:

$$\sigma_j = \min_{i \to j} (\sigma_i + D_{ij}) \qquad (20)$$

where: $\sigma_j$ = the duration of the shortest path at node j

$D_{ij}$ = the duration of the path between nodes i and j.

The following are the main steps in the formulation of Elmaghraby's algorithm used in LOGNAP:

STEP (a) - identify the minimum possible terminal number node for an activity. Note that this is the initial node plus one, since the terminal node of an activity must exceed the initial node number to satisfy the I-J rule.

STEP (b) - set the optimum predecessor to zero and the path cost to infinity.

STEP (c) - consider each activity to see if its terminal node is the minimum possible, and if its initial node of the activity is not less than the initial node for this path. If not, continue Step (c) for the remaining activities.

STEP (d) - test if the path length from the initial node to this node is minimal. If so, establish the new minimal path length and optimal predecessor. Continue at Step (c) with the remaining activities.

STEP (e) - when all activities have been considered, establish a new initial node, and continue at Step (a). When all nodes greater than the initial node of the path have been examined, the length of the shortest path is known.

STEP (f) - the nodes on the shortest path are found by working backwards from the terminal node to the origin using the optimal predecessors of each node.

# 4. RESULTS AND DISCUSSION

To illustrate the application of shortest path network analysis to the selection of least-cost forest harvesting systems, several LOGNAP runs were made. These runs investigated the optimal and near-optimal harvesting systems under a set of standard environmental conditions. The effects that changes in these conditions had on the systems selected were also studied.

The expanded network diagram shown in Figure 7 was used for the runs. The network consisted of 133 activities and 77 nodes, and had 848 alternative paths. The basic data for the activities comprising the network including initial and final node numbers, activity descriptions and various costing variables outlined in Section 3.2 are summarized in Appendix D.

The standard environmental conditions common to all activities were separated into economic and operating variables. These standard parameters are summarized in Table 7. Except where noted in the following sections these values for the variables were used.

The sections which follow describe the results of the runs and suggestions for future work.

Table 7. Values of Variables Describing Standard Environmental Conditions Used in the Sample Analysis.

ECONOMIC VARIABLES

| | |
|---|---|
| Interest Rate (%) | 12 |
| Fuel Price ($/litre) | 0.22 |
| Repair Time In-Shift (% of total repair time) | 85 |
| Fringe Benefit Factor (% of hourly wage) | 35 |
| Insurance Rate Factor (% of unrecovered value) | 3 |
| Rate of Lost Utility (%/year) | 30 |

OPERATING VARIABLES

| | |
|---|---|
| Tree Species | Black Spruce |
| Average Tree Size (DBH in cm) | 18 |
| Stand Density ($m^3$/hectare) | 100 |
| Average Primary Transport Distance (m) | 150 |
| Hauling Distance - Road Class 1 (km) | 96 |
| Hauling Distance - Road Class 2 (km) | 16 |
| Hauling Distance - Road Class 3 (km) | 3 |
| Average Slope (%) | 0 |

## 4.1 Optimal and Near-Optimal Harvesting Systems

LOGNAP was used to select the 50 least-cost forest harvesting system from the 848 possible alternatives. Appendix E.1 contains the complete computer output for this run.

Fifty paths were selected so as to minimize computing time and storage requirements. It was felt that identifying additional systems beyond this number would provide little benefit other than satisfying curiosity. If needed, the costs of non-selected systems can be calculated using the activity duration data from LOGNAP's output.

On the Hewlett-Packard 9845B mini-computer used for this research, a run time of approximately two hours was required to trace the 50 paths. This relatively long computer run time is attributable to the small size of the computer rather than algorithmic inefficiences. A test run of LOGNAP on a larger computer, an H.-P. 1000, suggests that run times several hundred times shorter can be attained with the programs.

Results of this run, specifically the range in woods costs within the top 50 systems and the actual systems selected, are discussed in the next two sections.

### 4.1.1 Wood Costs

Wood cost data for the first 50 least-cost alternative harvesting systems are plotted in Figure 9. The systems are ranked in ascending order based on wood costs measured in dollars per cubic metre of tree-length wood unloaded at the mill site. Note that these costs are based solely on machine rates and do not include such costs as roads, supervision and overheads.

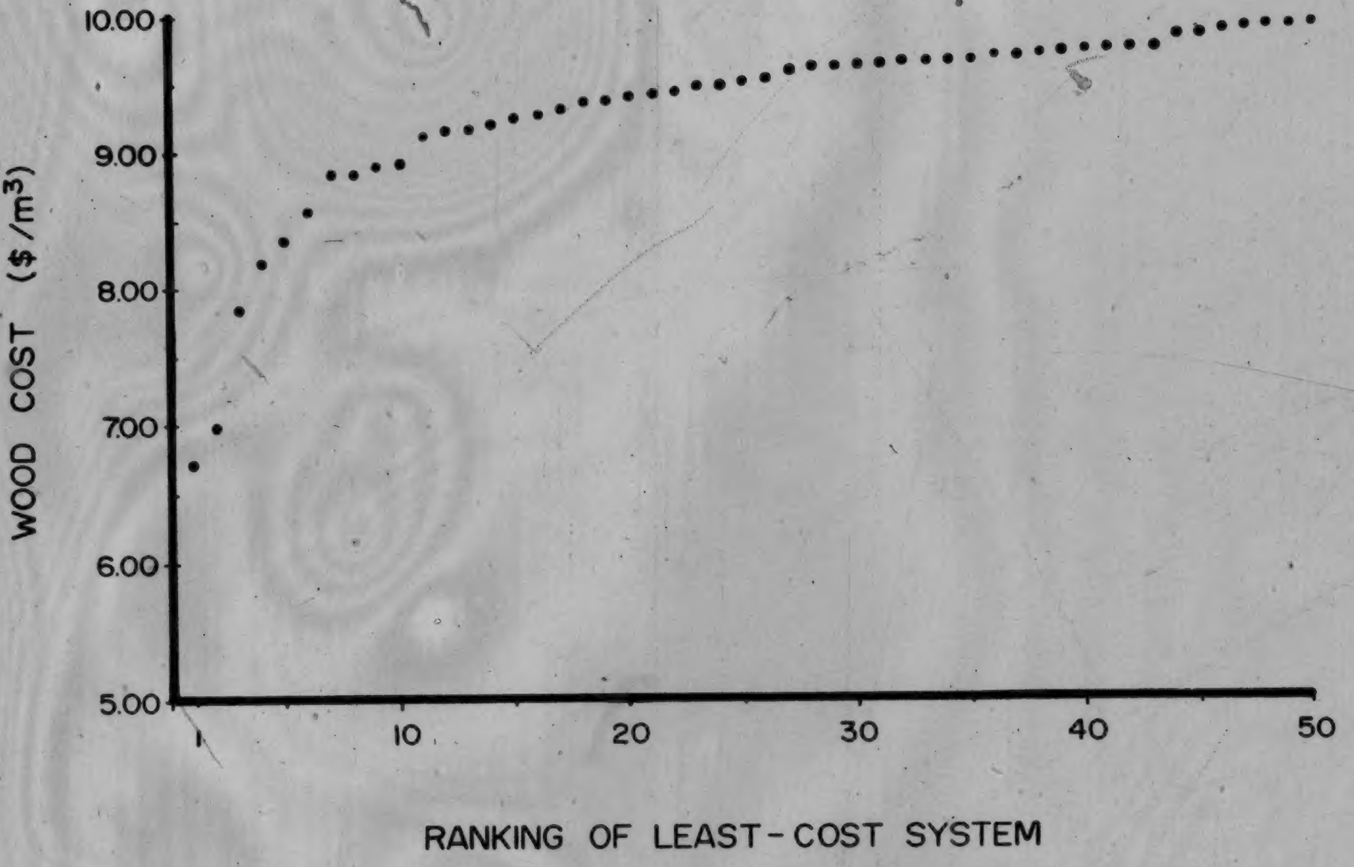

Figure 9. Wood costs for the 50 least-cost alternative harvesting systems.

The cost curve in Figure 9 indicates that the two systems which produced the lowest wood costs are significantly cheaper than those subsequently selected for the standard conditions. The two best systems have wood costs 10 percent lower, about \$1/m$^3$, less than the third best system. Perhaps more important however is that the range in wood costs between System 10 and System 50 is also about \$1/m$^3$. A difference of only \$0.40/m$^3$ existed in the wood costs of System 26 and System 50.

In other words, under the conditions modelled in this run, wood costs are relatively insensitive to the actual system used. The majority of alternative systems are not significantly cheaper than other systems. Figure 10 shows that 80% of the alternative systems produce only about one third of the total difference in woods costs between System 1 and System 50.

Under these circumstances, the ability of shortest path network analysis to identify both optimal and non-optimal is a great advantage. The penalty costs of operating some machines outside their optimum range appear to be so small that a company might be prepared to absorb them rather than make additional capital expenditures. As such identifying the ranking and costs of sub-optimal systems may be of equal importance to finding the least-cost system.

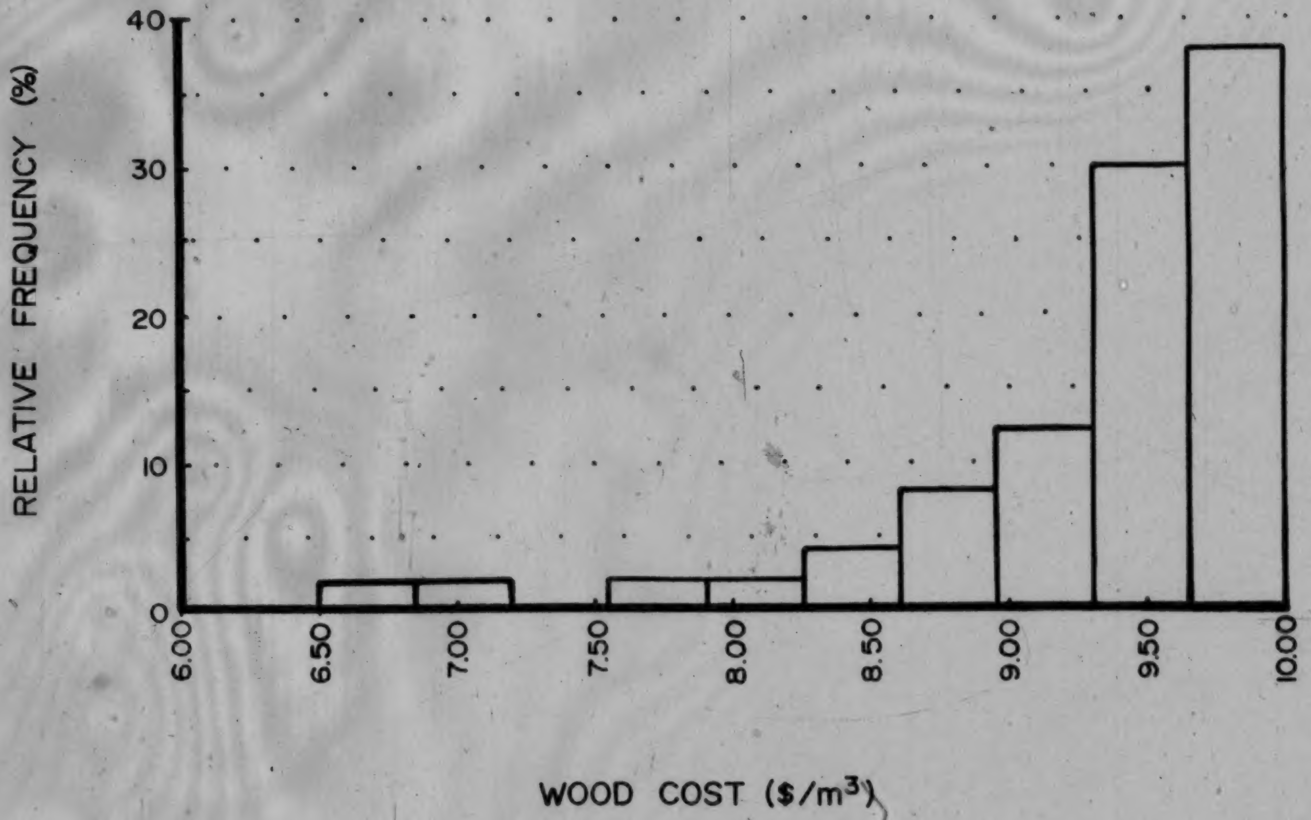

Figure 10. Frequency distribution of wood costs among the 50 least-cost alternative systems.

### 4.1.2 Systems Selected

Table 8 summarizes the alternative subsystems among the 50 least-cost systems as a means of identifying the types of equipment which offer the best alternatives. Total frequency of selection for each subsystem are located at the bottom of the table. Note that the subsystems which occur between landing and mill have not been included since they are common to all systems.

The majority of selected systems involve the subsystems of felling and bunching, primary transport of bunched full-trees, and delimbing at roadside. No particular piece of equipment appears to be superior for fulfilling the fell and bunch function. Grapple and clam-bunk skidders appeared to be superior for the primary transport stage. Roadside delimbing with flails was clearly superior but the model does not include any penalty costs for poor delimbing quality.

The first five least-cost systems utilize a "swathing" machine presently under development which fells and primary transports combined with roadside flail delimbing. This machine offers significantly lower wood costs than presently available systems under the conditions where the machine can operate. Somewhat surprising was the low ranking of systems using the similar feller-forwarder concept (34th) although the machine has recently enjoyed considerable commercial success.

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Table 8. Main Subsystems in the 50 Least-Cost Alternative Harvesting Systems.

| SYSTEM RANKING | FELL | FELL & BUNCH | FELL, DELIMB & BUNCH | FELL & DELIMB | FELL & PRIMARY TRANS. | FELL, DEL., BUN. & P.T. | DELIMB (STUMPSIDE) | PRIMARY TRANS. (FT. BUNCH) | DELIMB & BUNCH (STUMPSIDE) | PRIMARY TRANS. (FT LOOSE) | PRIMARY TRANS. (TL LOOSE) | PRIMARY TRANS. (TL BUNCH) | DELIMB (ROADSIDE) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | x | | | | | | | | x |
| 2 | | | | | x | | | | | | | | x |
| 3 | | | | | x | | | | | | | | x |
| 4 | | | | | x | | | | | | | | x |
| 5 | | | | | x | | | | | | | | x |
| 6 | | x | | | | | | x | | | | | x |
| 7 | | x | | | | | | x | | | | | x |
| 8 | | x | | | | | | x | | | | | x |
| 9 | | x | | | | | | x | | | | | x |
| 10 | | x | | | | | | x | | | | | x |
| 11 | | x | | | | | | x | | | | | x |
| 12 | | x | | | | | | x | | | | | x |
| 13 | | x | | | | | | x | | | | | x |
| 14 | | x | | | | | | x | | | | | x |
| 15 | | x | | | | | x | | | | | x | |
| 16 | | x | | | | | | x | | | | | x |
| 17 | | x | | | | | | x | | | | | x |
| 18 | x | | | | | | | | | x | | | x |
| 19 | | | | x | | | | | | | x | | |
| 20 | | x | | | | | | x | | | | | x |
| 21 | | x | | | | | | x | | | | | x |
| 22 | | x | | | | | | x | | | | | x |
| 23 | | | | | x | | | | | | | | x |
| 24 | | x | | | | | x | | | | | x | |
| 25 | | x | | | | | x | | | | | x | |
| 26 | | x | | | | | | x | | | | | x |
| 27 | | x | | | | | | x | | | | | x |
| 28 | x | | | | | | | | x | | | x | |
| 29 | | x | | | | | x | | | | | x | |
| 30 | x | | | | | | | | | x | | | x |
| 31 | | | x | | | | | | | | | x | |
| 32 | | x | | | | | | x | | | | | x |
| 33 | | x | | | | | | x | | | | | x |
| 34 | | | | | x | | | | | | | | x |
| 35 | | x | | | | | | x | | | | | x |
| 36 | | x | | | | | | x | | | | | x |
| 37 | | x | | | | | | x | | | | | x |
| 38 | x | | | | | | | | | x | | | x |
| 39 | | x | | | | | x | | | | | x | |
| 40 | | | | | x | | | | | | | | x |
| 41 | | x | | | | | x | | | | | x | |
| 42 | | x | | | | | | x | | | | | x |
| 43 | | x | | | | | | x | | | | | x |
| 44 | x | | | | | | | | x | | | x | |
| 45 | | x | | | | | x | | | | | x | |
| 46 | | | x | | | | | | | | | x | |
| 47 | | | x | | | | | | | | | x | |
| 48 | | x | | | | | | x | | | | | x |
| 49 | | x | | | | | | x | | | | | x |
| 50 | | x | | | | | | x | | | | | x |
| TOTAL | 5 | 33 | 3 | 1 | 8 | 0 | 7 | 26 | 2 | 3 | 1 | 12 | 37 |

## 4.2 Sensitivity Analysis

The operating environments of forest harvesting systems are extremely variable. Economic conditions are continually changing. The physical environment is seldom constant even within a cut-block. Other conditions set by management decisions are subject to change.

Given this variable operating environment, identifying the optimal and near-optimal systems is of limited value since the model parameters are fixed for any run. These parameters may be the best estimates of present and future operating conditions, but they remain estimates with uncertainty associated with them. Thus the solution of a practical problem is incomplete without investigating how changes in the operating environment affect the optimal solution.

Sensitivity analysis, the study of how the parameters affect the optimal solution can be undertaken using LOGNAP. To illustrate how sensitivity analysis could be applied, several potentially important parameters, energy prices and tree size, were studied. Sensitivity analysis was also used to determine the optimal operating zones for harvesting systems.

### 4.2.1 Energy Prices

The effects of energy prices were chosen for evaluation because of their volatile nature and potential scarcity. An analysis of the historical impact of energy expenditures on wood costs suggested that wood costs increase at about half the rate of energy price hikes on a constant dollar basis. This figure was used to account for the impact of different fuel prices on all components of machine costs. Fuel prices were then varied from $0.165/litre and $0.44/litre, the upper figure being approximately double present costs while holding the other standard variables constant. Results of these LOGNAP runs are summarized in Appendix E.2.

The selection sequence of the standard systems was greatly affected by changes in fuel prices. Table 9 compares the selection sequence of alternative harvesting systems at various levels of fuel costs. The systems are numbered based on their ranking under the standard conditions.

While the three least-cost systems maintained their rankings over the range of prices studied, some systems proved to be very sensitive to energy price changes. For example, a manual, "cut and skid" system which ranked 19th under standard conditions was the fourth cheapest system when fuel prices were doubled. A system that was unranked when fuel cost $0.22/litre was selected eighth when fuels cost $0.44/litre. Other so-called manual systems showed similar dramatic improvements in their rankings.

The overall effect of a doubling in energy prices was a 67% increase in wood costs for the least-cost system. The overall shape of the system cost curve (Figure 10) remained similar but was shifted upwards with higher energy prices.

Undertaking sensitivity analysis with LOGNAP was easy. Only one equation and one standard variable required changes to determine the effects of energy prices on the selection of the least-cost systems.

Table 9. Changes in the Selection Sequence of the Standard Systems under Different Fuel Prices

| Fuel Prices | | | | | |
|---|---|---|---|---|---|
| 25% Lower ($0.165/L) | Standard ($0.22/L) | 25% Higher ($0.275/L) | 50% Higher ($0.33/L) | 75% Higher ($0.385/L) | Double ($0.44/L) |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | 3 | 3 | 3 | 3 | 3 |
| 4 | 4 | 4 | 4 | 4 | 19 |
| 5 | 5 | 5 | 5 | 19 | 4 |
| 6 | 6 | 6 | 19 | 5 | 5 |
| 8 | 7 | 7 | 6 | 6 | 6 |
| 7 | 8 | 8 | 7 | 7 | - |
| 9 | 9 | 9 | 8 | 18 | 18 |
| 10 | 10 | 19 | 9 | 9 | 7 |
| 11 | 11 | 10 | 10 | 8 | 9 |
| 13 | 12 | 11 | 18 | 10 | 8 |
| 12 | 13 | 18 | 11 | - | 10 |
| 14 | 14 | 12 | 12 | 12 | 28 |
| 15 | 15 | 13 | 13 | 11 | 30 |
| 16 | 16 | 14 | - | 28 | 38 |
| 17 | 17 | 16 | 14 | 30 | 12 |
| 20 | 18 | 15 | 16 | 38 | 11 |
| 22 | 19 | 17 | 28 | 13 | - |
| 21 | 20 | 20 | 15 | 16 | - |

### 4.2.2 Average Tree Size

One of the most important operating variables affecting system performance is average tree size. It enters activity duration calculations in the cycle time equations for many machines and in the hourly productivity equation (#18). To study the sensitivity of systems selection to this variable, a series of LOGNAP runs were made varying tree diameters at breast height between 12 and 30 centimeters. Results of these runs are summarized in Appendix E.3.

Figure 11 illustrates the observed effects of average tree size on the least-cost system selection. While the swather with roadside flail delimbing remained optimal over most of the range in tree size, a tractor-mounted shear system was the least-cost system with trees greater than 26 cm DBH. This system however, exhibited great sensitivity to average tree size.

A swather-based system with a roll delimber was optimal with very small trees though very marginally ($0.01/m$^3$). In actual practice, it is unlikely that this system would be utilized since a stand of trees with a 12 cm diameter is on the borderline of merchantability.

An advantage of the shortest path network analysis approach to system selection is apparant from this example of sensitivity analysis. Prediction equations of non-linear form are easily incorporated into the model without the need for approximation using line segments as mathematical programming approaches would require. Three or four segments would be necessary to accurately describe the cost curve of the tractor-mounted shear system, but only one equation was needed using LOGNAP.

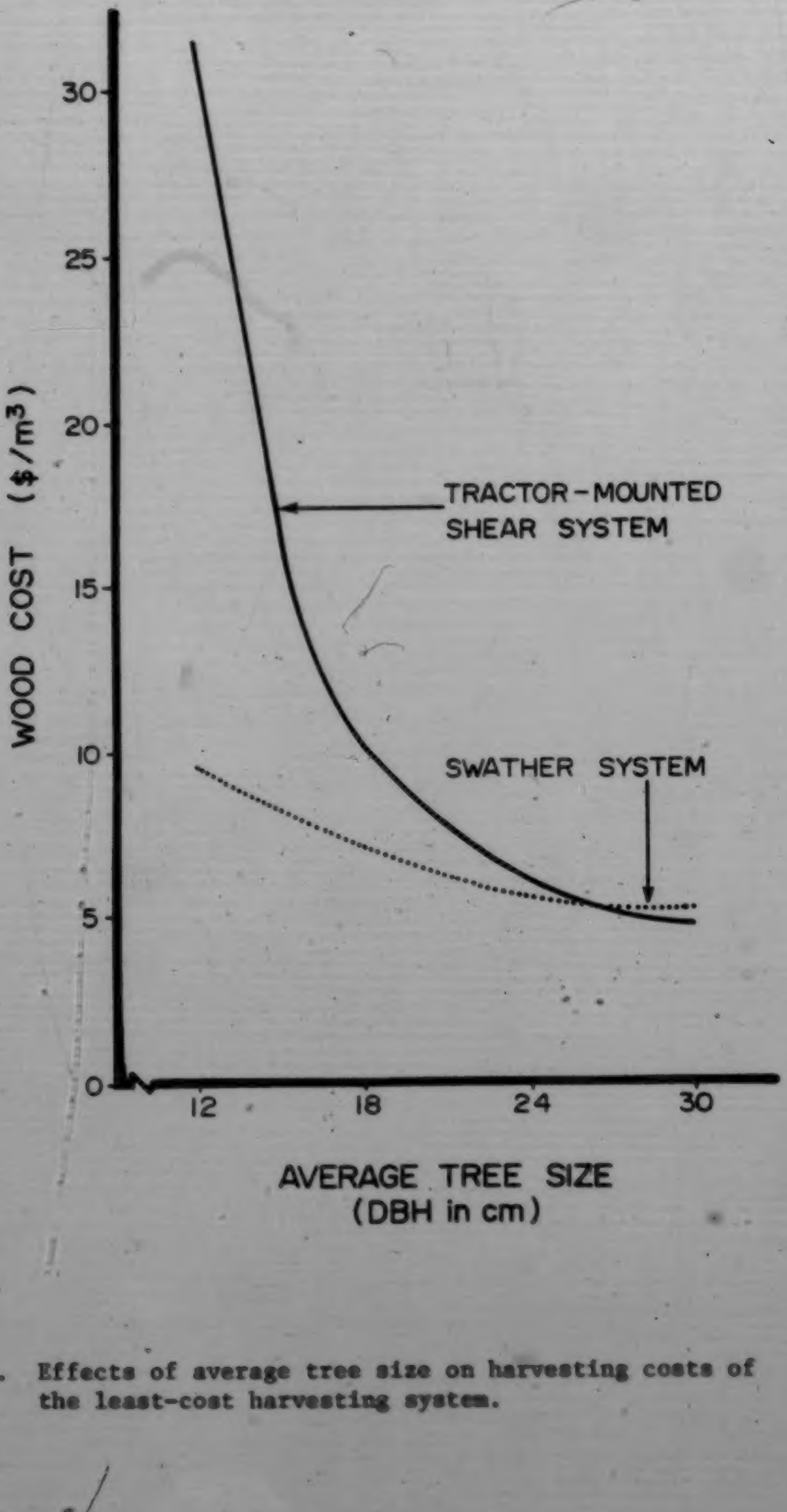

Figure 11. Effects of average tree size on harvesting costs of the least-cost harvesting system.

### 4.2.3 Optimal Operating Zones

One potential application of sensitivity analysis with LOGNAP is to identify the optimal operating zones for harvesting systems. To illustrate such a use, sensitivity analyses were conducted on a range of average tree sizes and stand densities. These parameters were varied across the range of conditions typically found in Eastern Canada: tree diameters at breast height from 12 to 30 centimeters and stand volumes from 60 to 180 cubic metres/hectare. The results of these LOGNAP runs are summarized in Appendix E.3.

Both stand parameters had a significant impact on the sequence of system selection. Many systems which had not been selected in the previous analyses became optimal or near-optimal. Over the range of parameters examined, wood costs more than doubled. Table 10 summarizes the wood costs for the three systems which became optimal over conditions studied.

Three systems were optimal for practical purposes under some combination of stand density and tree size. A fourth system was optimal with very small trees as discussed in the previous section but will not be considered. The swather-roadside flail system was the least-cost system over much of the range. A tractor-mounted shear with tracked cable skidding and roadside flail delimbing was optimal with large trees and low densities. A manual fell, tracked cable skidder and roadside flail system was the least-cost system with an average tree diameter of 18 cm and a stand density of 60 $m^3$/ha. Figure 12 combines the response surfaces of the three systems. The shaded areas outline the conditions under which each system is optimal.

Table 10. Wood Costs (\$/m$^3$) for the Least-Cost Harvesting Systems Under Varying Stand Volumes and Average Tree Sizes.

| | | | STAND VOLUME (m$^3$/ha) | | | |
|---|---|---|---|---|---|---|
| | | | 60 | 100 | 140 | 180 |
| AVERAGE TREE SIZE (DBH in cm) | 12 | SWATHER | 10.79 | 9.62 | 9.12 | 8.84 |
| | 18 | | 7.88 | 6.71 | 6.21 | 5.93 |
| | 24 | | 6.78 | 5.62 | 5.12 | 4.84 |
| | 30 | | 6.49 | 5.38 | 5.19 | 4.60 |
| | 12 | TRACTOR-MOUNTED SHEAR, TRACKED CABLE SKID | 32.73 | 31.43 | 30.64 | 30.11 |
| | 18 | | 10.69 | 10.27 | 9.97 | 9.73 |
| | 24 | | 6.16 | 6.05 | 5.93 | 5.83 |
| | 30 | | 4.84 | 4.79 | 4.74 | 4.70 |
| | 12 | MANUAL FELL, TRACKED CABLE SKID | 29.82 | 29.82 | 29.82 | 29.82 |
| | 18 | | 9.70 | 9.70 | 9.70 | 9.70 |
| | 24 | | 6.09 | 6.09 | 6.09 | 6.09 |
| | 30 | | 5.15 | 5.15 | 5.15 | 5.15 |

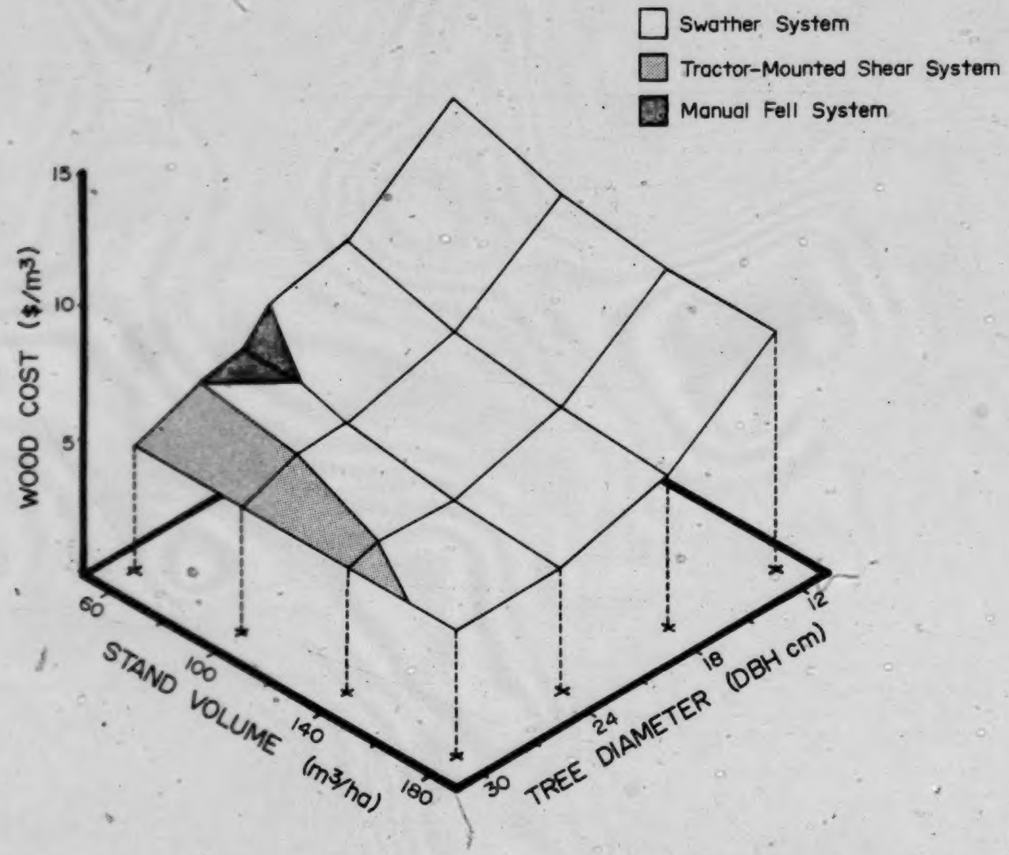

Figure 12. Least-cost harvesting systems under varying stand volumes and average tree sizes.

## 4.3 Program Modifications and Extensions

Several modifications could be made to LOGNAP to improve the accuracy and usefulness of the program. The following are some areas for further work.

### 4.3.1 Costing Models

The costing model used in this research while more realistic than many used in the past *e.g.* [15] could still be improved. The treatment of equipment salvage values and repair costs in particular need refinement.

The assumption that a machine's salvage value equals what is in effect its undepreciated worth is not realistic in the present used-machinery market. Price escalations, largely due to a high inflation rate, have recently been so rapid that salvage values of equipment trade-ins may equal or exceed the original purchase price. Studies of logging equipment salvage values over time are not available.

A similar situation exists with repair costs. Though some companies can establish long-term repair costs, these are not generally available. This research assumed a long-term average cost for repairs. While this approach gives reasonable estimates of total expenditures, it may not provide a good picture of the actual timing of these costs. With a cash flow-type model, timing is a critical concern.

The development of an after-tax cash model should be considered, although machine costing is presently done on a before-tax basis in the Canadian logging industry. This approach would provide a better approximation of the company's actual cash flow.

The programming of several alternative costing models so that users could select the approach they wish to use may be desireable. Cash flow models might also incorporate estimates of future costs for things such as energy and inflation.

### 4.3.2 Productivity Equations

While the equations used to predict productivity represent the best available information, they were frequently found to be deficient. In most cases for example, no relationship had been established for slope or soil conditions though such must exist and exercise a major influence on the system selected. Most machine studies do not examine sufficient stand and terrain conditions to quantify the impact of these variables on cycle times.

In other cases the equations used were taken from studies of prototype machines and old models. Whether these relationships apply to present equipment is debatable. Certainly the establishment of accurate relationships between cycle times and various operating conditions is necessary to minimize the selection of non-optimal systems.

An alternative would be to model the physical relationships involved with a working machine and derive cycle time estimates by calculation rather than from observation.

### 4.3.3 Data Set Edit Routine

No changes were made in the basic data set during the sample application. As presently programmed, such changes could only be made by complete re-entry of the data using the INPUT program. A routine for editing the data set would be a useful addition to LOGNAP. This would permit the updating of purchase prices and labour rates, and evaluation of the impact of machine specific variables on systems selection.

### 4.3.4 Uncertain Activity Durations

To compensate for imprecise costing and productivity estimates, uncertainty could be incorporated into the estimates of activity duration. A probability distribution for the estimated cost of each activity using optimistic, likely and pessimistic estimates of duration as is done with PERT could be established. The expected cost and a variance measure for any system could then be obtained. If a large variance is associated with the shortest path, or only small differences exist in the length of the shortest and sub-shortest paths, improved system selection might be achieved by considering risk and minimizing the uncertainty.

### 4.3.5 Negative Activity Durations

One advantage of Yen's algorithm is that the concept of a negative activity duration can be handled. This would permit compensation for non-equivalent activities to be included within the network.

For example shear damage to tree butts may produce a significant loss of value (10-15%) for fibre destined for lumber [50], but little loss in value if intended for pulping. Penalizing shearing equipment using a negative duration would place both the equipment and product on an equivalent base. Similarly an expanded network of all types of harvesting systems could be prepared with a compensating activities to place all systems to a common basis. Limbing quality is another area where the concept of penalty costs could be incorporated.

### 4.3.6 Optimal Operating Layouts

Comparisons made with LOGNAP at present are based on all systems operating under the same logging layouts. While this may be necessary for selecting systems for particular situations, costs when all equipment is operating under optimal layouts can be useful particularly for planning purposes.

The treatment of average primary transport distance in the present model illustrates the problem. A constant distance was assumed for all primary transport equipment. However if this distance is not optimal for a particular machine, any system using that machine could produce wood at a lower cost with appropriate layout changes. At the same time, road costs could be incorporated in the model.

Modification of the program to permit selection of systems operating under optimal layouts is desirable.

### 4.3.7 System Balancing

LOGNAP identifies the equipment which would produce the lowest cost wood. It does not consider the problem of how many of each machine type is necessary to meet organizational goals. Further work could incorporate the optimal system in a mixed-integer mathematical programming model which balances the system within overall company objectives. Several forest harvesting simulators which are capable of modeling most systems e.g. [69; 152] could also be utilized to balance the system.

# 5. SUMMARY AND CONCLUSIONS

Alternative methods of delivering tree-length wood to a processing plant were outlined as a directed, acrylic network diagram. Completed operations were represented by nodes in the network. Arcs joining the nodes described possible sequences of activities for fulfilling the system's function.

The duration of each activity, measured in dollars per cubic metre of wood produced, was estimated using the hourly costs and productivity of the equipment and labour involved. Hourly costs were calculated on an annual equivalent basis using a before-tax cash flow model of capital and operating costs. Productivity estimates used cycle-time prediction equations derived from time studies, and parameters such as tree and load sizes to characterize the operating environment and the equipment.

A package of computer programs was developed to select the optimal (least-cost) and near-optimal systems using shortest path network analysis. The systems were identified using Yen's algorithm [159] to find a specified number of shortest paths. The shortest distance and nodes on a path between some node and the network's terminal node were found using a dynamic programming algorithm proposed by Elmaghraby [42].

Of the alternatives modelled, those systems using a feller-forwarder based on the swathing principle produced the lowest wood cost under most conditions. A system consisting of a swather and flail delimbing at roadside was the least-cost system over a wide range of energy prices, tree sizes and stand volumes. A tractor-mounted shear system produced the lowest cost wood under conditions of low stand volume and large tree size. The widely used manual felling system was the least-cost system with trees diameters of about 24 cm and low stand volumes.

Shortest path network analysis proved to be an excellent means of identifying least-cost forest harvesting systems. A network diagram in itself is a useful aid to visualizing the sequence of activities and overlooked alternatives for meeting a system's function. Given the small differences observed between the wood costs of most systems, the identification of more than the least-cost system is highly desirable. Sensitivity analysis is easily and quickly completed.

Perhaps the greatest advantage of shortest path network analysis is that a great number of alternatives can be defined in terms of standard estimating equations, minimizing the time spent defining the problem and maximizing the understanding of non-technical personnel.

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# APPENDIX A

## PRICE INDICES USED TO DEFLATE COST STATISTICS

### A.1 Consumer Price Index

The Consumer Price Index (CPI) is applied to total annual wages, so that employee earnings can be compared on an equal buying-power basis over the time frame. CPI values for 1960 to 1978 are tabulated in Table A.1. These values were applied to calculate the "Average Wage" column in Table 1.

### A.2 Forestry Machinery and Equipment Index

The Forestry Machinery and Equipment Index (FMEI) is applied to capital expenditures on logging activities to permit the comparison of capital investments made at different times on an equal basis. FMEI values are tabulated in Table A.1. These values were used to equate the capital expenditures in Figure 4.

### A.3 Implicit Price Indices for Gross National Product

The Implicit Price Indices (IPI) permit the comparison of costs composed of many indirectly related items. The effects of all variables included in the Gross National Product are averaged, permitting unrelated costs to be compared on a common basis. IPI values are tabulated in Table A.1. These values were applied to standardize wood costs in Figure 3, and the productivity indices in Table 2.

Table A.1. Price Indices for the Years 1960 to 1978 [146; 148; 151].

| YEAR | CONSUMER PRICE INDEX | FORESTRY MACHINERY AND EQUIPMENT INDEX | IMPLICIT PRICE INDEX |
|---|---|---|---|
| 1960 | 74.3 | 83.6 | 71.0 |
| 1961 | 75.0 | 84.8 | 72.4 |
| 1962 | 75.9 | 87.3 | 73.4 |
| 1963 | 77.2 | 90.4 | 74.8 |
| 1964 | 78.6 | 96.4 | 76.6 |
| 1965 | 80.5 | 100.7 | 79.1 |
| 1966 | 83.5 | 101.0 | 82.6 |
| 1967 | 86.5 | 94.6 | 85.9 |
| 1968 | 90.0 | 91.5 | 88.7 |
| 1969 | 94.1 | 94.2 | 92.6 |
| 1970 | 97.2 | 97.4 | 96.9 |
| 1971 | 100.0 | 100.0 | 100.0 |
| 1972 | 104.8 | 102.8 | 104.8 |
| 1973 | 112.7 | 107.1 | 113.4 |
| 1974 | 125.0 | 122.2 | 129.4 |
| 1975 | 138.5 | 142.2 | 148.8 |
| 1976 | 148.9 | 149.0 | 163.3 |
| 1977 | 160.8 | 161.7 | 171.4 |
| 1978 | 175.2 | 180.7 | 182.3 |

# APPENDIX B

## EQUATIONS USED TO CALCULATE CYCLE TIMES

### B.1 Formulae for Common Variables

Percentage of grapple area occupied by full-tree stems [82].

$$\text{PACKINGFT (decimal \%)} = 0.188 + 0.0213 \times \text{DSH (cm)}$$

Percentage of grapple area occupied by tree-length stems [82].

$$\text{PACKINGTL (decimal \%)} = 0.440 + 0.0213 \times \text{DSH (cm)}$$

Average travel distance (DIST)

$$\begin{aligned}\text{DIST (m)} &= \text{Wander Factor} \times \text{Average Primary Transport Distance (m)}\\ &= 1.4 \times \text{APTD}\end{aligned}$$

Number of trees per hectare (NTPH)

$$\text{NTPH} = \frac{\text{Merchantable Volume per Hectare (m}^3\text{/ha)}}{\text{Merchantable Volume per Tree (m}^3\text{)}}$$

Machine payload [154; pp. 60-64]

$$\text{Payload} = \frac{T\ (TE - R \times TW)}{FS - T \times R \times P}$$

where: $T$ = traction coefficient

$TE$ = tractive effort (kg)

$FS$ = skidding coefficient

$R$ = rolling resistance coefficient

$TW$ = tare weight (kg)

$P$ = proportion of payload supported by skidder

Number of trees per cycle

$$NT = \frac{\text{Payload (kg)}}{\text{Weight per Tree (kg)}}$$

or

$$= \text{Integer}\left(\frac{\text{Rated Boom Capacity at Maximum Reach (kg)}}{3 \times \text{Weight per Tree (kg)}}\right)$$

or

$$= \text{Integer}\left(\frac{4 \times \text{Grapple Area (cm}^2) \times \text{PACKING}}{\pi \times \text{DBH}^2 \text{ (cm)}}\right)$$

## B.2 Equations for Various Tree Parameters

Regression equations for the tree parameters needed in the cycle time prediction equations are contained in Tables B.1 through B.5 for the four main softwood species of Eastern Canada.

Table B.1. Regression Equations for Calculating Stump Diameter (15 cm height) [2, p. 8-11].

| | | |
|---|---|---|
| Jack Pine<br>(*Pinus banksiana* Lamb.) | $DSH_{pj} = DBH + 0.230 \times DBH$ | $r^2 = 0.995$ |
| Black Spruce<br>(*Picea mariana* (Mill.) B.S.P.) | $DSH_{sb} = DBH + 0.253 \times DBH$ | $r^2 = 0.996$ |
| White Spruce<br>(*Picea glauca* (Moench) Voss.) | $DSH_{sw} = DBH + 0.269 \times DBH$ | $r^2 = 0.993$ |
| Balsam Fir<br>(*Abies balsamea* (L.) Mill.) | $DSH_{fb} = DBH + 0.230 \times DBH$ | $r^2 = 0.997$ |

---

Table B.2. Regression Equations for Calculating Merchantable Tree Length (m) [76, p. 68].

| | | |
|---|---|---|
| Jack Pine | $ML_{pj} = 9.745 \times DBH^{0.228}$ | $r^2 = 0.648$ |
| Black Spruce | $ML_{sb} = 0.819 \times DBH^{0.918}$ | $r^2 = 0.790$ |
| White Spruce | $ML_{sw} = 1.687 \times DBH^{0.704}$ | $r^2 = 0.855$ |
| Balsam Fir | $ML_{fb} = 0.855 \times DBH^{0.870}$ | $r^2 = 0.785$ |

Table B.3. Regression Equations for Calculating Green Weights (kg) of Tree-Lengths [76, p. 64].

| | | |
|---|---|---|
| Jack Pine | $WTTL_{pj} = 0.217 \times DBH^{2.301}$ | $r^2 = 0.978$ |
| Black Spruce | $WTTL_{sb} = 0.153 \times DBH^{2.345}$ | $r^2 = 0.952$ |
| White Spruce | $WTTL_{sw} = 0.111 \times DBH^{2.425}$ | $r^2 = 0.983$ |
| Balsam Fir | $WTTL_{fb} = 0.063 \times DBH^{2.650}$ | $r^2 = 0.963$ |

---

Table B.4. Regression Equations for Calculating Green Weights (kg) of Full-Trees [76, p. 64].

| | | |
|---|---|---|
| Jack Pine | $WTFT_{pj} = 0.346 \times DBH^{2.214}$ | $r^2 = 0.977$ |
| Black Spruce | $WTFT_{sb} = 0.330 \times DBH^{2.209}$ | $r^2 = 0.955$ |
| White Spruce | $WTFT_{sw} = 0.331 \times DBH^{2.217}$ | $r^2 = 0.984$ |
| Balsam Fir | $WTFT_{fb} = 0.215 \times DBH^{2.382}$ | $r^2 = 0.968$ |

Table B.5. Regression Equations for Calculating Merchantable Tree Volume ($m^3$) [76, p. 66].

| | | |
|---|---|---|
| Jack Pine | $MV_{pj} = 1.8 \times 10^{-4} \times DBH^{2.406}$ | $r^2 = 0.981$ |
| Black Spruce | $MV_{sb} = 1.1 \times 10^{-4} \times DBH^{2.502}$ | $r^2 = 0.947$ |
| White Spruce | $MV_{sw} = 0.9 \times 10^{-4} \times DBH^{2.547}$ | $r^2 = 0.979$ |
| Balsam Fir | $MV_{fb} = 1.1 \times 10^{-4} \times DBH^{2.515}$ | $r^2 = 0.968$ |

## B.3 Cycle Time Equations

1. Feller-buncher, wheeled, shear - Forano BJ-20 [131]

$$CT(1) = 50 + 212 \times MV$$

2. Feller-buncher, tracked, shear - Drott 40 [127]

$$CT(2) = 40 + 21.2 \times MV$$

3. Feller-buncher, multiple-tree shear - Koehring KFB4 [85]

$$NT = INT\left(\frac{1135}{3 \times WTFT}\right) + 1$$

$$CT(3) = 49.4 - 7.2 \times NT + 42.4 \times MV$$

4. Feller-buncher wheeled, shear - Melroe Bobcat 1075

$$CT(4) = 43 + \frac{3460}{NTPH}$$

5. Feller-buncher, wheeled, saw - Kockums 880 [10; 46]

$$CT(5) = 40 \times e^{(DBH/1065)}$$

6. Feller-buncher, tracked, saw - Drott 40 [50; 127]

$$CT(6) = 40 + 113 \times MV$$

7. Feller-buncher, tracked, auger - Drott 40 [51; 127]

$$CT(7) = 40 + 113 \times MV$$

8. Feller-buncher, wheeled, multiple-tree saw - Hydro-Ax Swather

$$NT = INT\left(\frac{1600}{3 \times WTFT}\right) + 1$$

$$CT(8) = 70 + 0.70 \times SLOPE - 7 \times NT$$

9.-16. Dummies

17. Fell - man with chain saw [154]

$$CT(17) = 0.650 \times DBH^{1.81}$$

18. Fell, tracked shear - Caterpillar D6 [29]

$$CT(18) = \frac{6000}{95.46 + 0.085 \times NTPH}$$

19. Fell, tracked saw - FMC 200 with feller-director [84]

$$CT(19) = 60 + 116.5 \times MV$$

20. Fell, tracked saw - Caterpillar D6 [29]

$$CT(20) = \frac{6000}{90 + 0.085 \times MV}$$

21.-24. Dummies

25. Delimb stumpside (loose) - Logma T-310 [129]

$$CT(25) = 27 + \frac{22725}{NTPH} + 24.7 \times MV$$

26. Delimb stumpside (loose) - Drott 40 with roll delimber [45]

$$CT(26) = 53 + 14 \times MV$$

27.-29. Dummies

30. Fell and delimb - man with chain saw [154]

$$CT(30) = 0.55 \times DBH^{1.81} + 0.17 \times DBH^{2.42}$$

31. Fell and delimb - John Deere 743 [49]

$$CT(31) = 58 + 0.86 \times ML$$

32.-33. Dummies

34. Fell, delimb and bunch - Timberjack TJ-30 [130]

$$CT(34) = 66 - 0.60 \times SLOPE + 102.4 \times MV$$

35. Fell, delimb and bunch - Koehring KFB4 with Timmins head [85; 45]

$$CT(35) = 66.4 + 14 \times MV$$

36. Fell, delimb and bunch - Drott 40 with Timmins head [45; 47]

$$CT(36) = 62 + 98 \times MV$$

37.-39. Dummies

40. Delimb stumpside (bunched) - Logma T-310 [129]

$$CT(40) = 35 + 102.4 \times MV$$

41. Delimb stumpside (bunched) - GLFP/NESCO flail [66]

$$CT(41) = 40$$

42. Delimb stumpside (bunched) - Drott 40 with Timmins head [45]

$$CT(42) = 30 + 38.5 \times MV$$

43.-45. Dummies

46. Primary transport (bunched full trees), wheeled, cable skidder - John Deere 540 [56]

$$\text{Payload} = \frac{0.55\ (6375 - 0.50 \times 7580)}{0.65 - 0.55 \times 0.5 \times 0.5} = 2775\ \text{kg}$$

$$\text{NT} = \text{INT}\ \left(\frac{2775}{\text{WTFT}}\right)$$

$$\text{CT}(46) = 32 + 229 \times \text{MV} + \frac{200 + 2.5 \times \text{DIST}}{\text{NT}}$$

47. Primary transport (bunched full trees), wheeled, cable skidder - John Deere 740 [56]

$$\text{Payload} = \frac{0.55\ (11365 - 0.50 \times 12135)}{0.65 - 0.55 \times 0.5 \times 0.5} = 5685\ \text{kg}$$

$$\text{NT} = \text{INT}\ \left(\frac{5685}{\text{WTFT}}\right)$$

$$\text{CT}(47) = 32 + 229 \times \text{MV} + \frac{200 + 2.5 \times \text{DIST}}{\text{NT}}$$

48. Primary transport (bunched full-trees), wheeled, grapple skidder - John Deere 540 [19]

$$\text{NT} = \text{INT}\ \left(\frac{4 \times 8082 \times \text{PACKINGFT}}{\pi \times \text{DBH}^2}\right)$$

$$\text{CT}(48) = 22.6 \times \text{MV} + \frac{322 + 2.5 \times \text{DIST}}{\text{NT}}$$

49. Primary transport (bunched full-trees), wheeled, grapple skidder - John Deere 740 [19]

$$\text{NT} = \text{INT}\ \left(\frac{4 \times 13935 \times \text{PACKINGFT}}{\pi \times \text{DBH}^2}\right)$$

$$\text{CT}(49) = 22.6 \times \text{MV} + \frac{400 + 2.5 \times \text{DIST}}{\text{NT}}$$

50. Primary Transport (bunched full-trees), wheeled, clam skidder - Timberjack 520 [128]

$$\text{NT} = \text{INT}\ \left(\frac{4 \times 32515 \times \text{PACKINGFT}}{\pi \times \text{DBH}^2}\right)$$

$$\text{CT}(50) = 162 \times \text{MV} + \frac{328 + 2.85 \times \text{DIST}}{\text{NT}}$$

51. Primary Transport (bunched full-trees), wheeled, forwarder - Koehring KF2 [85; 48; 65]

$$\text{NT} = \text{INT}\ \left(\frac{29000}{\text{WTFT}}\right)$$

$$\text{CT}(51) = 35 + \frac{52 + 5.84 \times \text{DIST}}{\text{NT}}$$

52. Primary Transport (bunched full-trees), tracked, cable skidder - FMC 200 [84; 132]

$$NT = INT\left(\frac{6200}{WTFT}\right)$$

$$CT(52) = \frac{1200 + 2.36 \times DIST}{NT}$$

53. Primary Transport (bunched full-trees), tracked, clam skidder - FMC 200 [84; 132]

$$NT = \left(\frac{4 \times 13285 \times PACKINGFT}{\pi \times DBH^2}\right)$$

$$CT(53) = \frac{1050 + 2.36 \times DIST}{NT}$$

54.-61. Dummies

62. Primary Transport (loose full-trees), wheeled, cable skidder - John Deere 540 [56]

$$NT = INT\left(\frac{2775}{WTFT}\right)$$

$$CT(62) = 40 + 229 \times MV + \frac{257 + 2.5 \times DIST}{NT}$$

63. Primary Transport (loose full-trees), wheeled, cable skidder - John Deere 740 [56]

$$NT = INT\left(\frac{5686}{WTFT}\right)$$

$$CT(63) = 40 + 229 \times MV + \frac{257 + 2.5 \times DIST}{NT}$$

64. Primary Transport (loose full-trees), wheeled, clam skidder - Timberjack 520 [128]

$$NT = INT\left(\frac{4 \times 32515 \times PACKINGFT}{\pi \times DBH^2}\right)$$

$$CT(64) = 200 \times MV + \frac{600 + 2.85 \times DIST}{NT}$$

65. Primary Transport (loose full-trees), wheeled forwarder - Koehring KF2 [85]

$$NT = INT\left(\frac{29000}{WTFT}\right)$$

$$CT(65) = 55 + \frac{52 + 5.84 \times DIST}{NT}$$

66. Primary Transport (loose full-trees), tracked, cable skidder - FMC 200 [84; 132]

$$\text{NT} = \text{INT}\left(\frac{6200}{\text{WTFT}}\right)$$

$$\text{CT}(66) = \frac{1350 + 2.36 \times \text{DIST}}{\text{NT}}$$

67. Primary Transport (loose full-trees), tracked, clam skidder - FMC 200 [84; 132]

$$\text{NT} = \text{INT}\left(\frac{4 \times 13285 \times \text{PACKINGFT}}{\pi \times \text{DBH}^2}\right)$$

$$\text{CT}(67) = \frac{1300 + 2.36 \times \text{DIST}}{\text{NT}}$$

68.-73. Dummies

74. Fell and Primary Transport, shear, skid - Timberjack 520 with head [128; 45]

$$\text{NT} = \text{INT}\left(\frac{4 \times 32515 \times \text{PACKINGFT}}{\pi \times \text{DBH}^2}\right)$$

$$\text{CT}(74) = 50 + \frac{1000 + 2.85 \times \text{DIST}}{\text{NT}}$$

75. Fell and Primary Transport, multiple-tree shear, forward - Koehring KFF [85; 48; 65]

$$\text{NT} = \text{INT}\left(\frac{29000}{\text{WTFT}}\right)$$

$$\text{CT}(75) = 49.4 + \frac{52 + 5.84 \times \text{DIST}}{\text{NT}} + 42.4 \times \text{MV}$$

$$- 7.2 \times \left(\text{INT}\left(\frac{1135}{3 \times \text{WTFT}}\right) + 1\right)$$

76. Fell and Primary Transport, multiple-tree saw, forward - Koehring KFF [85]

$$\text{NT} = \text{INT}\left(\frac{29000}{\text{WTFT}}\right)$$

$$\text{CT}(76) = 49.4 + \frac{52 + 5.84 \times \text{DIST}}{\text{NT}} + 55 \times \text{MV}$$

$$- 7.2 \times \left(\text{INT}\left(\frac{1135}{3 \times \text{WTFT}}\right) + 1\right)$$

77. Fell and Primary Transport, saw, forward - PAPCO Swather

$$\text{CT}(77) = 10000/(1.02 \times \text{NTPH})$$

78.-81. Dummies

82. Primary Transport (loose tree-lengths), wheeled, cable skidder - John Deere 540 [56]

$$\text{Payload} = \frac{0.55\ (6375 - 0.50 \times 7580)}{0.55 - 0.55 \times 0.50 \times 0.60} = 3690 \text{ kg}$$

$$\text{NT} = \text{INT}\left(\frac{3690}{\text{WTTL}}\right)$$

$$\text{CT(82)} = 30 + 229 \times \text{MV} + \frac{257 + 2.5 \times \text{DIST}}{\text{NT}}$$

83. Primary Transport (loose tree-lengths), wheeled cable skidder - John Deere 740 [56]

$$\text{Payload} = \frac{0.55\ (11365 - 0.50 \times 12135)}{0.55 - 0.55 \times 0.50 \times 0.60} = 7570 \text{ kg}$$

$$\text{NT} = \text{INT}\left(\frac{7570}{\text{WTTL}}\right)$$

$$\text{CT(83)} = 30 + 229 \times \text{MV} + \frac{257 + 2.5 \times \text{DIST}}{\text{NT}}$$

84. Primary Transport (loose tree-lengths), wheeled grapple skidder - John Deere 540 [19]

$$\text{NT} = \text{INT}\left(\frac{4 \times 8082 \times \text{PACKINGTL}}{\pi \times \text{DBH}^2}\right)$$

$$\text{CT(84)} = 22.6 \times \text{MV} + \frac{600 + 2.5 \times \text{DIST}}{\text{NT}}$$

85. Primary Transport (loose tree-lengths), wheeled, clam skidder - Timberjack 520 [128]

$$\text{NT} = \text{INT}\left(\frac{4 \times 32515 \times \text{PACKINGTL}}{\pi \times \text{DBH}^2}\right)$$

$$\text{CT(85)} = 175 \times \text{MV} + \frac{600 + 2.85 \times \text{DIST}}{\text{NT}}$$

86. Primary Transport (loose tree-lengths), wheeled forwarder - Koehring KF2 [85]

$$\text{NT} = \text{INT}\left(\frac{29000}{\text{WTTL}}\right)$$

$$\text{CT(86)} = 55 + \frac{52 + 5.84 \times \text{DIST}}{\text{NT}}$$

87. Primary Transport (loose tree-lengths), tracked, cable skidder - FMC 200 [84; 132]

$$NT = INT\left(\frac{6200}{WTTL}\right)$$

$$CT(87) = \frac{1350 + 2.36 \times DIST}{NT}$$

88. Primary Transport (loose tree-lengths), tracked, clam skidder - FMC 200 [84; 132]

$$NT = INT\left(\frac{4 \times 13285 \times PACKINGTL}{\pi \times DBH^2}\right)$$

$$CT(88) = \frac{1300 + 2.36 \times DIST}{NT}$$

89.-95. Dummies

96. Primary Transport (bunched tree-lengths), wheeled, cable skidder - John Deere 540 [56]

$$NT = INT\left(\frac{3690}{WTTL}\right)$$

$$CT(96) = 30 + 229 \times MV + \frac{200 + 2.5 \times DIST}{NT}$$

97. Primary Transport (bunched tree-lengths), wheeled, cable skidder - John Deere 740 [56]

$$NT = INT\left(\frac{7570}{WTTL}\right)$$

$$CT(97) = 30 + 229 \times MV + \frac{200 + 2.5 \times DIST}{NT}$$

98. Primary Transport (bunched tree-lengths), wheeled, grapple skidder - John Deere 540 [56]

$$NT = INT\left(\frac{4 \times 8082 \times PACKINGTL}{\pi \times DBH^2}\right)$$

$$CT(98) = 22.6 \times MV + \frac{322 + 2.5 \times DIST}{NT}$$

99. Primary Transport (bunched tree-lengths), wheeled, grapple skidder - John Deere 740 [56]

$$NT = INT\left(\frac{4 \times 13935 \times PACKINGTL}{\pi \times DBH^2}\right)$$

$$CT(99) = 22.6 \times MV + \frac{400 + 2.5 \times DIST}{NT}$$

100. Primary Transport (bunched tree-lengths), wheeled, clam skidder - Timberjack 520 [128]

$$NT = INT\left(\frac{4 \times 32515 \times PACKINGTL}{\pi \times DBH^2}\right)$$

$$CT(100) = 162 \times MV + \frac{328 + 2.85 \times DIST}{NT}$$

101. Primary Transport (bunched tree-lengths), wheeled forwarder - Koehring KF2 [85]

$$NT = INT\left(\frac{29000}{WTTL}\right)$$

$$CT(101) = 35 + \frac{52 + 5.84 \times DIST}{NT}$$

102. Primary Transport (bunched tree-lengths), tracked, cable skidder - FMC 200 [84; 132]

$$NT = INT\left(\frac{6200}{WTTL}\right)$$

$$CT(102) = \frac{1200 + 2.36 \times DIST}{NT}$$

103. Primary Transport (bunched tree-lengths), tracked, clam skidder - FMC 200 [84; 132]

$$NT = INT\left(\frac{4 \times 13285 \times PACKINGTL}{\pi \times DBH^2}\right)$$

$$CT(103) = \frac{1050 + 2.36 \times DIST}{NT}$$

104.-111. Dummies

112. Delimb roadside - Logma T-310 [129]

$$CT(112) = 38 + 10.6 \times MV$$

113. Delimb roadside - Harricana [52]

$$CT(113) = 45$$

114. Delimb roadside - Koehring KBL

$$CT(114) = 50$$

115. Delimb roadside - Drott 40 with Timmins roll delimber [47]

$$CT(115) = 20 + 49.4 \times MV$$

116. Delimb roadside - Hydro Ax 500 flail [53]

$$CT(116) = 18$$

117. Delimb roadside - Hydro Ax flail system [53]

$$CT(117) = 20$$

118.-121. Dummies

122. Loader spreading bunch for delimbing - Tanguay 14030 [53]

$$CT(122) = 20$$

123. Delimbing touch-up - man with chain saw

$$CT(123) = 15$$

124. Harvest and primary transport - Koehring KTL [85]

$$NT = INT\left(\frac{20000}{WTTL}\right)$$

$$CT(124) = 75 + \frac{52 + 5.84 \times DIST}{NT}$$

125. Harvest and primary transport - Koehring KFF with Timmins head [47; 85]

$$NT = INT\left(\frac{25000}{WTTL}\right)$$

$$CT(125) = 54 + 49 \times MV + \frac{300 + 5.84 \times DIST}{NT}$$

126.-127. Dummies

128. Load, tracked - Caterpillar 235 [81]

$$NT = INT\left(\frac{4 \times 1000 \times PACKINGTL}{\pi \times DBH^2}\right)$$

$$CT(128) = \frac{47.7}{NT}$$

129. Dummy

130. Secondary transport, double load on semi-trailer [81]

$$NT = INT\left(\frac{41000}{WTTL}\right)$$

$$CT(130) = \frac{190 + 86 \times DISTRC1 + 144 \times DISTRC2 + 355 \times DISTRC3}{NT}$$

131. Dummy

132. Unload - Rago Wagner [81]

$$NT = INT\left(\frac{41000}{WTTL}\right)$$

$$CT(132) = \frac{300}{NT}$$

133. Dummy

# APPENDIX C

# COMPUTER PROGRAMS

## C.1 Program Listings

The programs contained in this appendix make up LOGNAP. Internal storage limitations of the Hewlett-Packard 9845B computer used in this work required that LOGNAP be broken into four segments.

The first program called "MAIN" is the master control program controlling the branching to the other modules, renumbering the nodes to satisfy the I-J rule, and outputting the final shortest path information.

The second program entitled "INPUT" is used to input and store the basic network description and costing information in a file. On the particular installation used in this work, data was stored on a floppy disk.

The third program called "ACTDUR" calculates the hourly cost at optimal machine life and hourly productivity for each activity. These values are used to calculate activity durations. All three values are outputted with a description of each activity for each set of standard variables. The cycle time equations contained in subroutine "PROD" are for the network used in this work.

The final program is "GSPNA". The programmed versions of Yen's and Elmaghraby's algorithms are contained in this routine.

```
10    ! ************************************************************************
20    !                LOGGING NETWORK ANALYSIS PROGRAM - MAIN
30    ! ************************************************************************
40    !  Developed by G.J. Garner (1979) from work by T.A. Preston (1966),
50    !  K.W. Lievers (1974), and G.J. Horne (1978).
60    ! ************************************************************************
70    !  Variables used in program MAIN.
80    !   Akl  -Array of dimension Np which contains the costs of the Kp least-
90    !         cost paths.  Akl(I) is the cost of the Ith least-cost path.
100   !   Device$-Code for the mass storage device containing the network data.
110   !   File$-Name of file containing the network data.
120   !   Icr  -Array of dimension Nn containing the key to the renumbering of
130   !         the nodes.  Icr(I) is the original node number corresponding to
140   !         the renumbered node I.
150   !   Ix   -Array of dimension Nn containing the original origin node
160   !         numbers.  Ix(I) is the original terminal node for activity I.
170   !   Js   -Array of dimension Np which stores the number of nodes in each
180   !         path in List A.  Js(I) is the number of nodes in the Ith least-
190   !         cost path.
200   !   Jx   -Array of dimension Nn containing the original terminal node
210   !         numbers.  Jx(I) is the original terminal node for activity I.
220   !   Kl   -Matrix of dimension (Np,Mp) containing the node numbers of the
230   !         path sequences in both Lists A and B.  Kl(I,J) is the node
240   !         number of the Jth node in the Ith least-cost path found to date.
250   !   Ksl  -Matrix of dimensions (Np,Mp) which is the least-cost paths in
260   !         terms of the original node numbers.  Ksl(I,J) is the original
270   !         node number of the Jth node in the Ith least-cost path.
280   !   Mn   -User inputted scaler which is the user's best estimate of the
290   !         maximum number of nodes in any of the Np least-cost paths.
300   !   Na   -User inputted scaler which is the number of activities in the
310   !         network.
320   !   Nn   -User inputted scaler which is the number of nodes in the network
330   !   Np   -User inputted scaler which is the number of least-cost paths
340   !         desired.
350   !   Nsv  -User inputted scaler which is the number of sets of variables.
```

```
360   ! ************************************************************************
370    OPTION BASE 1
380    COM Na,Nn,Mn,Np,Nsv,Num,File$[6],Device$[6]
390    COM Ix(250),Jx(250),Ic(250),Jc(250),Icr(250)
400    COM Ak1(50),At(250),Js(50),Kh(25),INTEGER K1(50,25)
410    DIM Ks1(50,30),B$(1)[50]
420   !  Input and output basic network parameters.
430    Answer$="MAYBE"
440    INPUT "Has the basic network data been stored (YES/NO)?",Answer$
450    Answer$=UPC$(TRIM$(Answer$))
460    IF Answer$[1,1]="Y" THEN 490
470    IF Answer$[1,1]<>"N" THEN 440
480      LOAD "INPUT",10
490 Target1:  Np=1
500    INPUT "How many least-cost paths are to be traced?",Np
510    Np=INT(Np)
520    IF Np<=50 THEN 570
530      BEEP
540      DISP "Maximum of 50 paths can be traced - TRY AGAIN."
550      WAIT 3000
560      GOTO 500
570    Nsv=1
580    INPUT "How many sets of variables are to be run?",Nsv
590    Nsv=INT(Nsv)
600    IF Answer$[1,1]="Y" THEN GOSUB Check_file
610    ASSIGN #1 TO File$&Device$
620    READ #1,1;Na,Nn,Mn
630   !  Input the nodes defining each activity and its description.
640    FOR I=1 TO Na
650      READ #1,I+1;Ix(I),Jx(I)
660      NEXT I
670    ASSIGN * TO #1
680   !  Renumber the nodes to conform to the I<J rule.
690    DISP "RENUMBERING NODES"
700    GOSUB Rnum
```

```
710   !  Make runs for the various sets of "V" variables.
720    Num=1
730   !  Calculate the activity durations and output the initial and final
740   !  nodes (unrenumbered), description and duration of each activity,
750   !  and find the Np least-cost paths through the network.
760 More_sets:  DISP "ACCESSING ACTDUR."
770    LOAD "ACTDUR",10
780   !  Determine the least-cost paths in terms of the original inputted node
790   !  numbers.
800 Target2:  MAT Ksl=ZER
810    FOR I=1 TO Np
820      FOR J=1 TO Mn
830        IF Kl(I,J)=0 THEN 860
840          Ksl(I,J)=Icr(Kl(I,J))
850        NEXT J
860      NEXT I
870   !  Output descriptions and costs of the Np least-cost paths.
880    DISP "OUTPUTTING PATHS"
890    PRINTER IS 7,4,WIDTH(132)
900    PRINT CHR$(27)&"&l6d51p51F"
910    I=0
920 Top:  GOSUB Heading
930 Output:  I=I+1
940    PRINT USING "#,8X,2D,6X,3D.2D,5X";I,Akl(I)
950    FOR J=1 TO Js(I)
960      PRINT USING "#,3D,2A";Ksl(I,J),", "
970      NEXT J
980    PRINT
990    IF (I MOD 25=0) AND (I<Np) THEN Top
1000   IF I MOD 5=0 THEN PRINT
1010   IF I<Np THEN Output
1020   PRINTER IS 16
1030   IF Num=Nsv THEN End
1040     Num=Num+1
1050     GOTO More_sets
```

```
1060 End:  DISP "RUN(S) COMPLETED."
1070   STOP
1080   END
1090 Heading:  PRINT PAGE,LIN(7);SPA(36),"SHORTEST PATHS THROUGH NETWORK"
1100   PRINT SPA(48);"RUN #";Num,LIN(2)
1110   PRINT SPA(7);"PATH      TOTAL  ";SPA(29);"NODES ON PATH"
1120   PRINT SPA(6);"NUMBER     COST"
1130   PRINT SPA(6);RPT$("-",90);LIN(1)
1140   RETURN
1150 Check_file:  ! THIS ROUTINE VERIFIES THE EXISTANCE OF THE DATA FILE.
1160   LINPUT "Enter mass storage unit specifier (eg. F8).",Device$
1170   Device$=TRIM$(Device$)
1180   IF Device$[1,1]<>":" THEN Device$=":"&Device$
1190   DISP "Place storage medium in device ";Device$;".  Press CONT."
1200   PAUSE
1210 Name:  LINPUT "Enter name of file to be used.",File$
1220   Length=LEN(File$)
1230   IF Length<6 THEN File$[1,6]=File$[1,Length]&RPT$(" ",6-Length)
1240   ASSIGN #1 TO File$[1,6]&Device$,N
1250   ASSIGN * TO #1
1260   ON N+1 GOTO Okay,No_file,Return1
1270 No_file:  DISP "File ";File$;" does not exist.  Try again."
1280   BEEP
1290   WAIT 3000
1300   GOTO Name
1310 Return1:  CAT TO B$(*);File$,1
1320   IF B$(1)[8,1]="*" THEN RETURN
1330     DISP "File ";File$;" is a PROG-type file.  Try again."
1340     BEEP
1350     WAIT 3000
1360     GOTO Name
1370 Okay:  RETURN
1380 Rnum:  ! NODE RENUMBERING ROUTINE - RNUM
1390   ! **********************************************************************
1400   !  This routine renumbers the nodes to satisfy the I<J rule, so that the
```

```
1410   !  initial node number Ic(I) is less than the terminal node number Jc(I)
1420   !  for all activities.
1430   !  ***********************************************************************
1440   !  Variables used in routine RNUM.
1450   !   I1   -Scaler used to set-up array Icr.
1460   !   Ic   -Array of dimension Na containing the renumbered origin nodes.
1470   !          Ic(I) is the renumbered origin node of activity I.
1480   !   Itest-Scaler used to test if other activities have the same initial
1490   !          node.
1500   !   Jc   -Array of dimension Na containing the renumbered terminal nodes.
1510   !          Jc(I) is the renumbered terminal node of activity I.
1520   !   J1   -Scaler equal to the terminal node of the highest unrenumbered
1530   !          activity.
1540   !   L    -Scaler used as a counter for finding the highest unrenumbered
1550   !          terminal node.
1560   !   N1   -Scaler equal to the highest unrenumbered terminal node.
1570   !   N2   -Scaler equal to the highest unrenumbered origin node.
1580   !*************************************************************************
1590   !  Zero array Ic, and initialize.
1600   MAT Ic=ZER
1610   N1=N2=Nn
1620   J1=Jx(Na)
1630   !  Set terminal nodes of all activities ending at the highest remaining
1640   !  node number to that node number.
1650   L=0
1660   L=L+1
1670   IF L>Na THEN 1880
1680   IF Jx(L)<>J1 THEN 1660
1690     Jc(L)=N1
1700   !  Test if other activities have the same initial node.
1710     Itest=Ix(L)
1720     Ix(L)=-Ix(L)
1730     FOR K=1 TO Na
1740       IF Ix(K)=Itest THEN 1660
1750       NEXT K
```

```
1760   !  Decrease N2 to the highest remaining initial node number.  Set new
1770   !  initial node numbers for activities having that initial node.
1780      N2=N2-1
1790      Ic(L)=N2
1800      FOR K=1 TO Na
1810        IF Ix(K)=Ix(L) THEN Ic(K)=N2
1820        NEXT K
1830   !  Check if all initial nodes have been set.
1840      IF N2-1=0 THEN 1950
1850      GOTO 1660
1860   !  Decrease N1 to highest remaining terminal node number, and set J1 equal
1870   !  to initial node of highest remaining unrenumbered activity.
1880    N1=N1-1
1890    FOR K=1 TO Na
1900      IF Ic(K)<>N1 THEN 1930
1910        J1=-Ix(K)
1920        GOTO 1650
1930      NEXT K
1940   !  Reset inputted initial node numbers to positive.
1950    MAT Ix=Ix*(-1)
1960   !  Form key for the renumbered nodes.
1970    FOR K=1 TO Na
1980      Icr(Jc(K))=Jx(K)
1990      NEXT K
2000    Icr(1)=1
2010    RETURN
```

```
10    ! **************************************************************************
20    !                   ACTIVITY DATA INPUT PROGRAM - INPUT
30    ! **************************************************************************
40    ! This program is for inputting, outputting and storing network parameter
50    ! and activity data for use in other segments of MAIN.
60    ! **************************************************************************
70       OPTION BASE 1
80       PRINTER IS 16
90       COM Na,Nn,Mn,Np,Nsv,Num,File$[6],Device$[6]
100      COM Ix(250),Jx(250),Ic(250),Jc(250),Icr(250)
110      COM Akl(50),At(250),Js(50),Kh(25),INTEGER Kl(50,25)
120      DIM B$(1)[50],Des$(250)[40],Marg$(1)[10],Shy(250),Pp(250),W(250)
130      DIM Gp(250),Lf(250),Hcf(250),Rcf(250),Mtbr(250),Oe(250),Alc(250)
140      Na=Nn=Mn=Np=Nsv=Correct=0
150 Activities:  INPUT "Enter # of activities in the network.",Na
160      Na=INT(Na)
170      IF Na<=250 THEN 200
180        GOSUB Too_many
190        GOTO Activities
200      IF Correct>0 THEN Check
210 Number_nodes:  INPUT "Enter # of nodes in the network.",Nn
220      Nn=INT(Nn)
230      IF Nn<=250 THEN 260
240        GOSUB Too_many
250        GOTO Number_nodes
260      IF Correct>0 THEN Check
270 Max_nodes:  INPUT "Estimate max. # of nodes on a path through network.",Mn
280      Mn=INT(Mn)
290      IF Mn<=25 THEN 320
300        GOSUB Too_many
310        GOTO Max_nodes
320 Check:  GOSUB Param1
330      Answer$="MAYBE"
340      INPUT "Is the above information correct (YES/NO)?",Answer$
350      Answer$=UPC$(TRIM$(Answer$))
```

```
360    IF Answer$[1,1]="Y" THEN Store
370    IF Answer$[1,1]="N" THEN Fix
380      GOSUB Wrong
390      GOTO 340
400 Too_many:  BEEP
410    DISP "Entered value exceeds the maximum permitted."
420    WAIT 2500
430    RETURN
440 Fix:  INPUT "Enter # of the network parameter to be corrected.",Correct
450    IF (Correct<1) OR (Correct>3) THEN 440
460      ON INT(Correct) GOTO Activities,Number_nodes,Max_nodes
470 Store:  GOSUB Check_file
480    IF N<>0 THEN CREATE File$&Device$,1+Na,140
490    ASSIGN #1 TO File$&Device$
500    PRINT #1,1;Na,Nn,Mn
510    ASSIGN #1 TO *
520 Enter_activity:  ! INPUT, CORRECT AND SAVE ACTIVITY DATA
530    PRINTER IS 16
540    FOR I=1 TO Na
550      PRINT PAGE,TAB(24),"DATA FOR ACTIVITY # -";I;LIN(3)
560      DISP "Initial node of activity #";I;
570      INPUT Ix(I)
580      PRINT "Initial node of activity .............";Ix(I)
590      DISP "Final node of activity #";I;
600      INPUT Jx(I)
610      PRINT "Final node of activity ...............";Jx(I)
620      DISP "Description of activity ";I;" (max. 40 characters)";
630      INPUT Des$(I)
640      PRINT "Activity description ................ ";Des$(I)
650      IF UPC$(TRIM$(Des$(I)))="DUMMY" THEN 840
660      DISP "Scheduled Hours Yearly, Purchase Price, and Hourly Wage";
670      INPUT Shy(I),Pp(I),W(I)
680      PRINT "Scheduled Hours Yearly (SMH) .........";Shy(I)
690      PRINT "Purchase Price ($) ...................";Pp(I)
700      PRINT "Hourly Wage ($/SMH) ..................";W(I)
```

```
710       DISP "Gross Engine Power, Load Factor, and Hydraulic Complexity
             Factor";
720       INPUT Gp(I),Lf(I),Hcf(I)
730       PRINT "Gross Engine Power (kW) ...............";Gp(I)
740       PRINT "Load Factor ...........................";Lf(I)
750       PRINT "Hydraulic Complexity Factor ...........";Hcf(I)
760       DISP "Repair Cost Factor, Mean Time Between Repairs, and Operational
             Efficiency";
770       INPUT Rcf(I),Mtbr(I),Oe(I)
780       PRINT "Repair Cost Factor ($/$1000 Pp/PMH) ...";Rcf(I)
790       PRINT "Mean Time Between Repairs (PMH) .......";Mtbr(I)
800       PRINT "Operational Efficiency (%) ............";Oe(I)
810       DISP "Licensing Cost";
820       INPUT Alc(I)
830       PRINT "Licensing Cost ($/year) ...............";Alc(I)
840       INPUT "Is the above information correct (YES/NO)?",Answer$
850       Answer$=UPC$(TRIM$(Answer$))
860       IF Answer$[1,1]="Y" THEN 900
870       IF Answer$[1,1]="N" THEN 550
880         GOSUB Wrong
890         GOTO 840
900       NEXT I
910     DISP "OUTPUTTING NETWORK PARAMETERS AND ACTIVITY DATA"
920     OVERLAP
930     PRINTER IS 7,4,WIDTH(132)
940     PRINT CHR$(27)&"&l6d51p51F"
950     Page=2
960     GOSUB Param
970     Page=Page+1
980     GOSUB Heading
990     FOR I=1 TO Na
1000      PRINT USING 1260;I,Ix(I),Jx(I),Des$(I)
1010      IF I MOD 5=0 THEN PRINT USING 1240
1020      IF I MOD 20<>0 THEN 1060
1030        PRINT USING 1250
```

```
1040        Page=Page+1
1050        GOSUB Heading
1060      NEXT I
1070    PRINT USING 1250
1080    ASSIGN #1 TO File$&Device$
1090    READ #1,2
1100    Page=Page+1
1110    GOSUB Print_out
1120    FOR I=1 TO Na
1130      PRINT USING 1290;I,Shy(I),Pp(I),W(I),Gp(I),Lf(I),Hcf(I),Rcf(I),Mtbr(I),
             Oe(I),Alc(I)
1140      IF I MOD 5=0 THEN PRINT
1150      IF I MOD 20=0 THEN GOSUB Print_out
1160      PRINT #1,I+1;Ix(I),Jx(I),Des$(I),Shy(I),Pp(I),W(I),Gp(I),Lf(I),Hcf(I),
             Rcf(I),Mtbr(I),Oe(I),Alc(I)
1170      NEXT I
1180    PRINT PAGE,PAGE
1190    ASSIGN #1 TO *
1200    PRINTER IS 16
1210    DISP "RETURNING TO MAIN."
1220    LOAD "MAIN",Target1
1230    END
1240    IMAGE 12X,4("|",10X),34X,"|"
1250    IMAGE 13X,77("-")
1260    IMAGE 12X,"|",3(3X,4D,3X,"|"),2X,40A,2X,"|"
1270    IMAGE 26X,50A,3D
1280    IMAGE //,44X,"COST VARIABLES",//
1290    IMAGE 7X,4D,7X,4D,5X,6D,4X,2D.2D,3X,3D,3(4X,Z.2D),4X,2D.D,4X,Z.2D,4X,4D
1300 Param:  PRINT PAGE,LIN(6),TAB(75);"APPENDIX D";SPA(4);"PAGE -";Page
1310 Param1:  PRINT LIN(2);TAB(40);"BASIC NETWORK PARAMETERS";LIN(2)
1320    PRINT USING 1270;"1. Number of activities in the network ..........";Na
1330    PRINT USING 1270;"2. Number of nodes in the network ...............";Nn
1340    PRINT USING 1270;"3. Estimated maximum number of nodes on a path ...";Mn
1350    RETURN
1360 Heading:  PRINT PAGE,LIN(7),TAB(75);"APPENDIX D";SPA(4);"PAGE -";Page
```

```
1370   PRINT LIN(2);TAB(45);"ACTIVITY DATA";LIN(2)
1380   Marg$=RPT$(" ",12)
1390   PRINT USING 1250
1400   PRINT Marg$;"| ACTIVITY |  INITIAL |  FINAL  |";SPA(18);"ACTIVITY";SPA(
          18);"|"
1410   PRINT Marg$;"|  NUMBER  |   MODE   |    NODE  |";SPA(17);"DESCRIPTION";
          SPA(16);"|"
1420   PRINT USING 1250
1430   PRINT USING 1240
1440   RETURN
1450 Print_out:  PRINT PAGE,LIN(7),TAB(75);"APPENDIX D";SPA(4);"PAGE -";Page
1460   Page=Page+1
1470   PRINT USING 1280
1480   PRINT SPA(5);"ACTIVITY  SCHEDULED  PURCHASE  HOURLY  GROSS   LOAD
          HYD.C.  REPAIR   MTBR   OPER.  LICENSE"
1490   PRINT SPA(5);" NUMBER      HOURS       PRICE     WAGE   POWER  FACTOR
          FACTOR  FACTOR          EFFEC     COST"
1500   PRINT SPA(5);RPT$("-",92),LIN(1)
1510   RETURN
1520 Check_file:  ! VERIFY DATA FILE'S EXISTANCE
1530   LINPUT "Enter mass storage unit specifier (eg. F8).",Device$
1540   Device$=UPC$(TRIM$(Device$))
1550   IF Device$[1,1]<>":" THEN Device$=":"&Device$
1560     DISP "Place storage medium in device ";Device$;".  Press CONT."
1570     PAUSE
1580 Name:  LINPUT "Enter name of file to be used.",File$
1590   Length=LEN(File$)
1600   IF Length<6 THEN File$=File$[1,Length]&RPT$(" ",6-Length)
1610   ASSIGN #1 TO File$&Device$,N
1620 Branch:  ON N+1 GOTO Okay,No_file,Return2
1630 Okay:  DISP "File ";File$;" exists.  Over-write file (YES/NO)";
1640   INPUT Answer$
1650   Answer$=UPC$(TRIM$(Answer$))
1660   IF Answer$[1,1]="Y" THEN RETURN
1670   IF Answer$[1,1]="N" THEN Name
```

```
1680      GOSUB Wrong
1690      GOTO Okay
1700 No_file:  DISP "File ";File$;" does not exist.  Create file (YES/NO)";
1710    INPUT Answer$
1720    Answer$=UPC$(TRIM$(Answer$))
1730    IF Answer$[1,1]="Y" THEN RETURN
1740    IF Answer$[1,1]="N" THEN Name
1750      GOSUB Wrong
1760      GOTO No_file
1770 Return2:  CAT TO B$(*);File$,1
1780    IF B$(1)[8,1]="*" THEN Protected
1790      BEEP
1800      DISP "File ";File$;" is a PROG-type file.  Try again.";
1810      WAIT 3000
1820      GOTO Name
1830 Protected:  DISP "File ";File$;" is protected.  What is the protect code";
1840    INPUT Protect$
1850    ASSIGN #1 TO File$&Device$,N,Protect$
1860    GOTO Branch
1870 Wrong:  BEEP
1880    DISP "Improper response - TRY AGAIN!"
1890    WAIT 3000
1900    RETURN
```

```
10      ! ***********************************************************************
20      !              ACTIVITY DURATION CALCULATING PROGRAM - ACTDUR
30      ! ***********************************************************************
40      !  This program calculates the activity durations ($/m) based on the
50      !  cost and productivity data calculated in subroutines COST and PROD,
60      !  and then stores them in array At.
70      ! ***********************************************************************
80      OPTION BASE 1
90      COM Na,Nn,Mn,Np,Nsv,Num,File$[6],Device$[6]
100     COM Ix(250),Jx(250),Ic(250),Jc(250),Icr(250)
110     COM Ak1(50),At(250),Js(50),Kh(25),INTEGER K1(50,25)
120     DIM Stcv(6),Stcv$(6)[46],Stov(8),Stov$(8)[46],Hcost(250),Hprod(250)
130     DIM Des$(250)[40]
140     Answer$="MAYBE"
150     !  Enter standard variables for this run.
160     PRINTER IS 16
170     Stcv$(1)="Interest Rate (%)"
180     Stcv$(2)="Fuel Price ($/liter)"
190     Stcv$(3)="Repair Time In-Shift (% of total repair time)"
200     Stcv$(4)="Fringe Benefit Factor (% of hourly wage)"
210     Stcv$(5)="Insurance Rate Factor (% of unrecovered value)"
220     Stcv$(6)="Rate of Lost Utility (%)"
230     CALL Enter(6,Stcv$(*),Stcv(*))
240     CALL List(6,Stcv$(*),Stcv(*),"",1,Num)
250     CALL Correct(Answer$)
260     IF Answer$[1,1]="Y" THEN 300
270       INPUT "Enter correction:  variable #, and value, or press CONT.",I,
             Stcv(I)
280       PRINT PAGE
290       GOTO 240
300     Stov$(1)="Species (Pj=1,Sb=2,Sw=3,Fb=4)"
310     Stov$(2)="Average Tree Size (DBH in cm)"
320     Stov$(3)="Stand Volume (m^3/hectare)"
330     Stov$(4)="Average Primary Transport Distance (meters)"
340     Stov$(5)="Hauling Distance - Road Class 1 (km)"
```

```
350   Stov$(6)="Hauling Distance - Road Class 2 (km)"
360   Stov$(7)="Hauling Distance - Road Class 3 (km)"
370   Stov$(8)="Average Slope (%)"
380   PRINT PAGE
390   CALL Enter(8,Stov$(*),Stov(*))
400   CALL List(8,Stov$(*),Stov(*),"",3,Num)
410   CALL Correct(Answer$)
420   IF Answer$[1,1]="Y" THEN 460
430     INPUT "Enter correction:  variable #, and value, or press CONT.",I,
           Stov(I)
440     PRINT PAGE
450     GOTO 400
460   OVERLAP
470   PRINTER IS 7,4,WIDTH(132)
480   PRINT CHR$(27)&"&l6d51p51F"
490   CALL List(6,Stcv$(*),Stcv(*),RPT$(" ",19),2,Num)
500   CALL List(8,Stov$(*),Stov(*),RPT$(" ",19),3,Num)
510   PRINTER IS 16
520   PRINT PAGE
530   !  Calculate activity costs ($/PMH) at optimal machine life.
540   CALL Cost(Stcv(*),Hcost(*),Des$(*))
550   !  Calculate activity productivity (m^3/PMH).
560   CALL Prod(Stov(*),Hprod(*))
570   !  Calculate and output activity durations ($/m^3).
580   FOR I=1 TO Na
590     IF Hprod(I)<>0 THEN At(I)=Hcost(I)/Hprod(I)
600     IF Hprod(I)=0 THEN At(I)=0
610     NEXT I
620   CALL Output(Des$(*),Hcost(*),Hprod(*),At(*),Na,Num)
630   DISP "ACCESSING GSPNA."
640   LOAD "GSPNA",10
650   END
660   SUB Cost(Stcv(*),Hcost(*),Des$(*))
670   ! ************************************************************************
680   !  This subroutine calculates the hourly cost ($/PMH) in constant dollar
```

```
690    !  terms for a machine kept for its optimal machine life.  Optimal life
700    !  is defined as the life which minimizes the total hourly costs with the
710    !  assumption that technological change limits machine life to a maximum
720    !  of 10 years.
730    !  ***********************************************************************
740    !  Variables used in subroutine COST not used in MAIN.
750    !   Aec  -Scaler equalling the total annual equivalent costs.
760    !   Aecc -Scaler equalling the annual equivalent capital costs.
770    !   Aeoc -Scaler equalling the annual equivalent operating costs.
780    !   Alc  -Annual licensing cost of the machine.
790    !   Apin -Array of dimension 10 containing the capital recovery factor.
800    !         Apin(I) is the factor for year I and interest rate "Interest".
810    !   Fc   -Fuel costs ($/PMH).
820    !   Gp   -Gross engine power (kW) of the machine.
830    !   Hcf  -Hydraulic complexity of the machine.
840    !   Hcost-Array of dimension Na.  Hcost(I) is the annual equivalent hourly
850    !         cost for the machine used in activity I at its optimal life.
860    !   Inc  -Insurance costs ($/PMH).
870    !   Lc   -Licensing costs ($/PMH).
880    !   Lf   -Average engine load factor of the machine.
890    !   Mc   -Manpower costs ($/PMH).
900    !   Mtbr -Mean time between repairs for the machine.
910    !   Oc   -Scaler equalling the hourly operating costs ($/PMH).
920    !   Oe   -Operational effectiveness of the machine.
930    !   Olc  -Oil and lubricant costs ($/PMH).
940    !   Oml  -Scaler used to identify the optimal machine life.
950    !   Phy  -Scaler equal to the number of productive hours yearly.
960    !   Pp   -Purchase price of the machine.
970    !   Rc   -Repair costs including both parts and labour ($/PMH).
980    !   Rcf  -Repair cost factor for the machine.
990    !   Shy  -Scheduled hours yearly for the machine.
1000   !   Spvoc-Scaler equalling the sum of the present value of the operating
1010   !         costs.
1020   !   Stcv -Array of dimension 6 which contains the standard cost variables
1030   !         used in calculating costs for all machines.  Stcv(i) is the
```

```
1040  !          interest rate (%).  Stcv(2) is the fuel price ($/l).  Stcv(3)
1050  !          if the repair time in-shift (% of total repair time).  Stcv(4)
1060  !          is the fringe benefit factor (% of hourly wage).  Stcv(5) is the
1070  !          insurance rate factor (% of unrecovered value).  Stcv(6) is the
1080  !          depreciation rate (%).
1090  !   U    -Utilization.
1100  !   W    -Employee's wage ($/SMH).
1110  ! *****************************************************************
1120   OPTION BASE 1
1130   COM Na,Nn,Mn,Np,Nsv,Num,File$[6],Device$[6]
1140   COM Ix(250),Jx(250),Ic(250),Jc(250),Icr(250)
1150   COM Akl(50),At(250),Js(50),Kh(25),INTEGER Kl(50,25)
1160   DIM Sv(10),Aec(10),Apin(10)
1170  !  Input cost variables for each activity.
1180   ASSIGN #1 TO File$&Device$            ! Open data file.
1190   READ #1,2                             ! Position to second record.
1200   Interest=Stcv(1)/100
1210   OVERLAP
1220   FOR I=1 TO Na
1230     READ #1,I+1,A,B,Des$(I),Shy,Pp,W,Gp,Lf,Hcf,Rcf,Mtbr,Oe,Alc
1240  !  Calculate components of the total cost for each activity.  Note that if
1250  !  Shy=0, the activity costs are set to Pp.  If Pp=0, then there are only
1260  !  labour costs.  Otherwise the cost equations are used.
1270     IF Shy<>0 THEN 1300
1280       Hcost(I)=Pp
1290       GOTO 1610
1300     IF Pp<>0 THEN 1330
1310       Hcost(I)=(1+Stcv(4)/100)*W
1320       GOTO 1610
1330     U=Mtbr/(1.1*Mtbr+Stcv(3)/100*1.8)*Oe
1340     Phy=Shy*U
1350     Lc=Alc/Phy
1360     Fc=.21*Gp*Lf*Stcv(2)
1370     Olc=Fc*Hcf
1380     Rc=Pp*Rcf/1000
```

```
1390    C=Lc+Fc+Olc+Rc
1400 !  Calculate salvage value, manpower costs, insurance cost based on the
1410 !  salvage value for the year, capital and operating costs on an annual
1420 !  equivalent basis, and optimal machine life.
1430    A1=Stcv(5)/100/Phy
1440    Oml=1
1450    Spvoc=0
1460    FOR J=1 TO 10
1470      Mc=W*(1+Stcv(4)/100)*1.05^(J-1)/U
1480      Sv(J)=Pp*(1-Stcv(6)/100)^J
1490      Inc=Sv(J)*A1
1500      Oc=C+Inc+Mc
1510      Spvoc=Spvoc+Oc/(1+Interest)^J
1520      Apin(J)=Interest*(1+Interest)^J/((1+Interest)^J-1)
1530      Aecc=((Pp-Sv(J))*Apin(J)+Sv(J)*Interest)/Phy
1540      Aeoc=Spvoc*Apin(J)
1550      Aec(J)=Aecc+Aeoc
1560      IF J=1 THEN 1580
1570        IF Aec(J)<=Aec(J-1) THEN Oml=J
1580      NEXT J
1590 !  Set-up array Hcost with activity costs.
1600    Hcost(I)=Aec(Oml)
1610    NEXT I
1620  ASSIGN #1 TO *
1630  SUBEND
1640 SUB Prod(Stov(*),Vpmh(*))
1650 ! ************************************************************************
1660 !  This subroutine calculates the hourly productivity (m^3/PMH) for the
1670 !  activities in the network.
1680 ! ************************************************************************
1690 !  Variables used in subroutine PROD not used in MAIN.
1700 !   Ct   -Array of dimension Na containing the activity cycle times (cmin)
1710 !   Dbh  -Scaler equalling the diameter breast height (cm).
1720 !   M1   -Scaler equalling the merchantable length of the tree (m).
1730 !   Mvpt -Scaler equalling the merchantable volume per tree (m^3).
```

```
1740  !  Nt   -Scaler equalling the number of trees that can be accumulated.
1750  !  Ntph -Scaler equalling the number of trees per hectare.
1760  !  Vpmh -Array of dimension Na containing the hourly productivity for
1770  !        for the activity.
1780  !  Wtft -Scaler equalling the green full-tree weight (kg).
1790  !  Wttl -Scaler equalling the green tree-length weight (kg).
1800  ! ********************************************************************
1810   OPTION BASE 1
1820   COM Na,Nn,Mn,Np,Nsv,Num,File$[6],Device$[6]
1830   COM Ix(250),Jx(250),Ic(250),Jc(250),Icr(250)
1840   COM Akl(50),At(250),Js(50),Kh(25),INTEGER Kl(50,25)
1850   DIM Ct(250)
1860  !  Input basic stand parameters.
1870   Dbh=Stov(2)
1880   ON Stov(1) GOTO Jack_pine,Black_spruce,White_spruce,Balsam_fir
1890 Jack_pine:  ! Calculate tree characteristics using regression equations.
1900   Mvpt=1.8/10^4*Dbh^2.406     ! R^2=0.981
1910   Wtft=.346*Dbh^2.214         ! R^2=0.977
1920   Wttl=.217*Dbh^2.301         ! R^2=0.978
1930   Ml=9.745*Dbh^.228           ! R^2=0.648
1940   Dsh=Dbh+.230*Dbh            ! R^2=0.995
1950   GOTO 2160
1960 Black_spruce:  ! Calculate tree characteristics using regression equations.
1970   Mvpt=1.1/10^4*Dbh^2.502     ! R^2=0.947
1980   Wtft=.330*Dbh^2.209         ! R^2=0.955
1990   Wttl=.153*Dbh^2.345         ! R^2=0.952
2000   Ml=.819*Dbh^.918            ! R^2=0.790
2010   Dsh=Dbh+.253*Dbh            ! R^2=0.996
2020   GOTO 2160
2030 White_spruce:  ! Calculate tree characteristics using regression equations.
2040   Mvpt=.9/10^4*Dbh^2.547      ! R^2=0.979
2050   Wtft=.331*Dbh^2.217         ! R^2=0.984
2060   Wttl=.111*Dbh^2.425         ! R^2=0.983
2070   Ml=1.687*Dbh^.704           ! R^2=0.855
2080   Dsh=Dbh+.269*Dbh            ! R^2=0.993
```

```
2090   GOTO 2160
2100 Balsam_fir:  ! Calculate tree characteristics using regression equations.
2110   Mvpt=1.8/10^4*Dbh^2.515       ! R^2=0.968
2120   Wtft=.215*Dbh^2.382           ! R^2=0.968
2130   Wttl=.063*Dbh^2.650           ! R^2=0.963
2140   Ml=.855*Dbh^.870              ! R^2=0.785
2150   Dsh=Dbh+.230*Dbh              ! R^2=0.997
2160   Packingft=.188+.0213*Dsh
2170   Packingtl=.440+.0213*Dsh
2180   Dist=1.4*Stov(4)
2190   Ntph=Stov(3)/Mvpt
2200   Ct(1)=50+21.2*Mvpt
2210   Ct(2)=40+21.2*Mvpt
2220   Nt=INT(1135/3/Wtft)+1
2230   Ct(3)=49.4-7.2*Nt+42.4*Mvpt
2240   Ct(4)=43+3460/Ntph
2250   Ct(5)=40*EXP(Dbh/1065)
2260   Ct(6)=40+113*Mvpt
2270   Ct(7)=40+113*Mvpt
2280   Nt=INT(1600/3/Wtft)+1
2290   Ct(8)=70+.70*Stov(8)-7*Nt
2300   Ct(17)=.65*Dbh^1.81
2310   Ct(18)=6000/(95.46+.085*Ntph)
2320   Ct(19)=60+116.5*Mvpt
2330   Ct(20)=6000/(90+.085*Ntph)
2340   Ct(25)=27+22725/Ntph+24.7*Mvpt
2350   Ct(26)=53+14*Mvpt
2360   Ct(30)=.55*Dbh^1.81+.17*Dbh^2.42
2370   Ct(31)=58+.86*Ml
2380   Ct(34)=66-.60*Stov(8)+102.4*Mvpt
2390   Ct(35)=66.4+14*Mvpt
2400   Ct(36)=62+98*Mvpt
2410   Ct(40)=35+102.4*Mvpt
2420   Ct(41)=40
2430   Ct(42)=30+38.5*Mvpt
```

```
2440   Nt=INT(2775/Wtft)
2450   Ct(46)=32+229*Mvpt+(200+2.5*Dist)/Nt
2460   Nt=INT(5685/Wtft)
2470   Ct(47)=32+229*Mvpt+(200+2.5*Dist)/Nt
2480   Nt=INT(4*8082*Packingft/PI/Dbh^2)
2490   Ct(48)=22.6*Mvpt+(322+2.5*Dist)/Nt
2500   Nt=INT(4*13935*Packingft/PI/Dbh^2)
2510   Ct(49)=22.6*Mvpt+(400+2.5*Dist)/Nt
2520   Nt=INT(4*32515*Packingft/PI/Dbh^2)
2530   Ct(50)=162*Mvpt+(328+2.85*Dist)/Nt
2540   Nt=INT(29000/Wtft)
2550   Ct(51)=35+(52+5.84*Dist)/Nt
2560   Nt=INT(6200/Wtft)
2570   Ct(52)=(1200+2.36*Dist)/Nt
2580   Nt=INT(4*13285*Packingft/PI/Dbh^2)
2590   Ct(53)=(1050+2.36*Dist)/Nt
2600   Nt=INT(2775/Wtft)
2610   Ct(62)=40+229*Mvpt+(257+2.5*Dist)/Nt
2620   Nt=INT(5685/Wtft)
2630   Ct(63)=40+229*Mvpt+(257+2.5*Dist)/Nt
2640   Nt=INT(4*32515*Packingft/PI/Dbh^2)
2650   Ct(64)=200*Mvpt+(600+2.85*Dist)/Nt
2660   Nt=INT(29000/Wtft)
2670   Ct(65)=55+(52+5.84*Dist)/Nt
2680   Nt=INT(6200/Nt)
2690   Ct(66)=(1350+2.36*Dist)/Nt
2700   Nt=INT(4*13285*Packingft/PI/Dbh^2)
2710   Ct(67)=(1300+2.36*Dist)/Nt
2720   Nt=INT(4*32515*Packingft/PI/Dbh^2)
2730   Ct(74)=50+(1000+2.85*Dist)/Nt
2740   Nt=INT(29000/Wtft)
2750   Ct(75)=49.4-7.2*(INT(1135/3/Wtft)+1)+42.4*Mvpt+(52+5.84*Dist)/Nt
2760   Nt=INT(29000/Wtft)
2770   Ct(76)=49.4-7.2*(INT(1135/3/Wtft)+1)+55*Mvpt+(52+5.84*Dist)/Nt
2780   Ct(77)=10000/(1.02*Ntph)
```

```
2790    Nt=INT(3690/Wttl)
2800    Ct(82)=30+229*Mvpt+(257+2.5*Dist)/Nt
2810    Nt=INT(7570/Wttl)
2820    Ct(83)=30+229*Mvpt+(257+2.5*Dist)/Nt
2830    Nt=INT(4*8082*Packingtl/PI/Dbh^2)
2840    Ct(84)=22.6*Mvpt+(600+2.5*Dist)/Nt
2850    Nt=INT(4*32515*Packingtl/PI/Dbh^2)
2860    Ct(85)=175*Mvpt+(600+2.85*Dist)/Nt
2870    Nt=INT(29000/Wttl)
2880    Ct(86)=55+(52+5.84*Dist)/Nt
2890    Nt=INT(6200/Wttl)
2900    Ct(87)=(1350+2.36*Dist)/Nt
2910    Nt=INT(4*13285*Packingtl/PI/Dbh^2)
2920    Ct(88)=(1300+2.36*Dist)/Nt
2930    Nt=INT(3690/Wttl)
2940    Ct(96)=30+229*Mvpt+(200+2.5*Dist)/Nt
2950    Nt=INT(7570/Wttl)
2960    Ct(97)=30+229*Mvpt+(200+2.5*Dist)/Nt
2970    Nt=INT(4*8082*Packingtl/PI/Dbh^2)
2980    Ct(98)=22.6*Mvpt+(322+2.5*Dist)/Nt
2990    Nt=INT(4*13935*Packingtl/PI/Dbh^2)
3000    Ct(99)=22.6*Mvpt+(400+2.5*Dist)/Nt
3010    Nt=INT(4*32515*Packingtl/PI/Dbh^2)
3020    Ct(100)=162*Mvpt+(328+2.85*Dist)/Nt
3030    Nt=INT(29000/Wttl)
3040    Ct(101)=35+(52+5.84*Dist)/Nt
3050    Nt=INT(6200/Wttl)
3060    Ct(102)=(1200+2.36*Dist)/Nt
3070    Nt=INT(4*13282*Packingtl/PI/Dbh^2)
3080    Ct(103)=(1050+2.36*Dist)/Nt
3090    Ct(112)=38+10.6*Mvpt
3100    Ct(113)=45
3110    Ct(114)=50
3120    Ct(115)=20+49.4*Mvpt
3130    Ct(116)=18
```

```
3140    Ct(117)=20
3150    Ct(122)=20
3160    Ct(123)=15
3170    Nt=INT(20000/Wttl)
3180    Ct(124)=75+(52+5.84*Dist)/Nt
3190    Nt=INT(25000/Wttl)
3200    Ct(125)=54+49*Mvpt+(300+5.84*Dist)/Nt
3210    Nt=INT(4*1000*Packingtl/PI/Dbh^2)
3220    Ct(128)=47.7/Nt
3230    Nt=INT(41000/Wttl)
3240    Ct(130)=(1900+86*Stov(5)+144*Stov(6)+355*Stov(7))/Nt
3250    Nt=INT(41000/Wttl)
3260    Ct(132)=300/Nt
3270    FOR I=1 TO Na
3280      IF Ct(I)<>0 THEN Vpmh(I)=6000*Mvpt/Ct(I)
3290      IF Ct(I)=0 THEN Vpmh(I)=0
3300      NEXT I
3310    SUBEND
3320 Wrong:  BEEP
3330    DISP "Improper response - TRY AGAIN!"
3340    WAIT 3000
3350    RETURN
3360    SUB Enter(N,Stv$(*),Stv(*))
3370    FOR I=1 TO N
3380      DISP Stv$(I);
3390      INPUT Stv(I)
3400      NEXT I
3410    SUBEND
3420    SUB Correct(Answer$)
3430    INPUT "Is the above information correct (YES/NO)?",Answer$
3440    Answer$=UPC$(TRIM$(Answer$))
3450    IF (Answer$[1,1]<>"Y") OR (Answer$[1,1]<>"N") THEN SUBEXIT
3460      GOSUB Wrong
3470      GOTO 3430
3480    SUBEND
```

```
3490   SUB List(N,Stv$(*),Stv(*),Marg$,X,M)
3500   DIM String$[52]
3510   IF X=1 THEN PRINT PAGE,SPA(17);"STANDARD VARIABLES FOR RUN";M;LIN(3);
          "ECONOMIC VARIABLES:",LIN(1)
3520   IF X=2 THEN PRINT PAGE,LIN(9),Marg$;SPA(17);"STANDARD VARIABLES FOR RUN";
          M;LIN(3);Marg$;"ECONOMIC VARIABLES:",LIN(1)
3530   IF X=3 THEN PRINT Marg$;"OPERATING VARIABLES:",LIN(1)
3540   FOR I=1 TO N
3550     String$=Stv$(I)&" "&RPT$(".",50-LEN(Stv$(I)))
3560     PRINT USING "K,2X,D.,2X,51A,DDZ.DD";Marg$;I;String$;Stv(I)
3570     NEXT I
3580   PRINT LIN(1)
3590   SUBEND
3600   SUB Output(Des$(*),Hcost(*),Hprod(*),At(*),Na,Num)
3610   PRINTER IS 7,4,WIDTH(132)
3620   PRINT CHR$(27)&"&l6d51p51F"
3630   I=0
3640   PRINT PAGE,LIN(9);SPA(37);"ACTIVITY DURATIONS FOR RUN";Num,LIN(3)
3650   PRINT SPA(11);" ACTIVITY   HOURLY    HOURLY     WOOD";SPA(15);"ACTIVITY
          DESCRIPTION"
3660   PRINT SPA(11);"  NUMBER     COST   PRODUCTION   COST"
3670   PRINT SPA(23);"($/PMH)  (m^3/PMH)  ($/m^3)"
3680   PRINT SPA(11);RPT$("-",85),LIN(1)
3690   I=I+1
3700   PRINT USING 3710;I,Hcost(I),Hprod(I),At(I),Des$(I)
3710   IMAGE 15X,3D,5X,3D.2D,3X,4D.2D,3X,DDZ.2D,5X,40A
3720   IF I=Na THEN 3770
3730   IF I MOD 5>0 THEN 3690
3740     PRINT
3750   IF I MOD 20=0 THEN 3640
3760     GOTO 3690
3770   PRINTER IS 16
3780   SUBEND
```

```
10     ! *********************************************************************
20     !          GENERAL SHORTEST PATH NETWORK ANALYSIS PROGRAM - GSPNA
30     ! *********************************************************************
40     !  This program determines the Np shortest paths through the network and
50     !  stores them in matrix K1 using Yen's algorithm.  The shortest paths are
60     !  determined by successively examining deviations from the J shortest
70     !  paths for J=1,2,3,...,Np-1.
80     ! *********************************************************************
90     !  Variables used in GSPNA not used in MAIN.
100    !   Akt  -Dummy scaler used to temporarily store a variable from Ak1.
110    !   Atp  -Array of dimension Na containing the pernament record of the
120    !         activity costs.  The array At is restored to its original values
130    !         at the beginning of each iteration by equating it to Atp.
140    !   Bnew -Scaler equal to the total cost of the latest generated path.
150    !   Icq  -Scaler used in the comparison of the newly generated path's cost
160    !         with the stored path costs in List B in Step II of the algoritm.
170    !   Id   -Flag which equals 0 if the newly generated path differs from
180    !         stored paths.  Id equals 1 if the path is not new.
190    !   In   -Scaler which takes the value I+1 when in Step I(A) the cost of
200    !         activity I is set to infinity.
210    !   Iq   -Flag used in Step I(A) for comparing subpaths.  Iq equals 1 if
220    !         the first I nodes of the most recent path in List A coincide in
230    !         sequence with the first I nodes of path J in List A.  Otherwise
240    !         Iq equals zero.
250    !   I5,I6-Scalers representing the node sequence in the (k-1)st best path.
260    !         They are used in the calculation of the root of a deviation from
270    !         this path.
280    !   Ja,Jb-Scalers used to denote sequential node numbers in calculating
290    !         the root and subpath for the latest deviation determined in
300    !         Step I(B).
310    !   Jk   -Scaler set equal to J1-1 for subpath checking in Step I(A).
320    !   J1   -Scaler containing the number of nodes in the path just added to
330    !         List A.
340    !   JJ1  -Scaler equalling the number of nodes in the most recent path
350    !         added to List B.
```

```
360   !   Ka   -Scaler used to identify activities when calculating the cost of
370   !         the root of the most recent addition to List A.
380   !   Kh   -Array of dimensions MN containing the sequence of nodes in the
390   !         spur of the most recently determined path.  Kh is produced by
400   !         subroutine Smsp.
410   !   Kr   -Array of dimension Mn containing the node numbers of the most
420   !         recently generated path - a candidate for List B.
430   !   Kt   -Array of dimension Mn which temporaily stores a path being
440   !         inserted into List B.
450   !   K2   -Scaler set equal to K-1 to denote the most recent addition to
460   !         List A in the search for deviations in Step I(A).
470   !   R    -Scaler equalling the cost of the root of the path found in Step
480   !         I(B).
490   !   S    -Scaler equalling the cost of the spur of the path found in Step
500   !         I(B).  S is produced in subroutine Smsp.
510   ! ****************************************************************
520   OPTION BASE 1
530   COM Na,Nn,Mn,Np,Nsv,Num,File$[6],Device$[6]
540   COM Ix(250),Jx(250),Ic(250),Jc(250),Icr(250)
550   COM Ak1(50),At(250),Js(50),Kh(25),INTEGER K1(50,25)
560   DIM Atp(250),Kr(25),Kt(25)
570   !  Copy the activity data into array Atp and zero matrix K1.
580   MAT Atp=At
590   MAT K1=ZER
600   !  Determine the least cost path through the network from node 1 to node
610   !  Nn.  If Np equals 1, nothing more is required.
620   J1=1
630   DISP "SEARCHING FOR PATH 1"
640   CALL Smsp(1,J1,S)
650   Js(1)=J1
660   FOR I=1 TO Mn
670     K1(1,I)=Kh(I)
680     NEXT I
690   Ak1(1)=S
700   IF Np=1 THEN Finish
```

```
710    !  Set array Ak1 to infinity.
720       FOR I=2 TO Np
730         Ak1(I)=1E20
740         NEXT I
750    !  The statements from here to the end determine the Np-1 least cost paths
760    !  through the network and store them in matrix K1.
770       FOR K=2 TO Np
780         DISP "SEARCHING FOR PATH ";K
790         BEEP
800    !  Reset array At to its original values at the start of each iteration.
810         MAT At=Atp
820         K2=K-1
830         Jk=J1-1
840    !  Step I of Yen's algorithm.  Certain activity costs in the network are
850    !  set to infinity in determining the minimum cost deviations from the
860    !  last path added to List A.
870         FOR I=1 TO Jk
880           J=1
890           Iq=1
900    !  Step I(A) of Yen's algorithm follows.  The subpath consisting of the
910    !  first I nodes of path K-1 is checked to see if they coincide with the
920    !  first I nodes of the previously identified best paths.  If so, the
930    !  duration of activities between nodes I and I+1 is set to infinity.
940           FOR Ij=1 TO I
950             IF K1(J,Ij)<>K1(K2,Ij) THEN Iq=0
960             NEXT Ij
970           IF Iq=1 THEN 1010
980           IF J>=K2 THEN 1160
990             J=J+1
1000            GOTO 890
1010          In=I+1
1020          Ia=K1(J,I)
1030          Ib=K1(J,In)
1040          Ka=1
1050          IF (Ia=Ic(Ka)) AND (Ib=Jc(Ka)) THEN 1100
```

```
1060          Ka=Ka+1
1070          IF Ka<=Na THEN 1050
1080            DISP "SOMETHINGS WRONG IN STEP I(A)."
1090            STOP
1100        At(Ka)=1E20
1110        GOTO 980
1120  !  Step I(B) of Yen's algorithm follows.  Subroutine Smsp is used to find
1130  !  the shortest path from node I to Nn.  the subpath from 1 to I is the
1140  !  root, and the subpath from I to Nn is the spur.  A new path must be
1150  !  found around the block created by setting the activity to infinity.
1160        Jj1=I
1170        CALL Smsp(Ia,Jj1,S)
1180        IF S>=1E10 THEN 1690
1190          R=0
1200          MAT Kr=ZER
1210        IF I=1 THEN 1420
1220        FOR I5=1 TO I-1
1230          I6=I5+1
1240          Ja=K1(K2,I5)
1250          Jb=K1(K2,I6)
1260          Kr(I5)=Ja
1270          Ka=1
1280          IF (Ja=Ic(Ka)) AND (Jb=Jc(Ka)) THEN 1330
1290            Ka=Ka+1
1300            IF Ka<=Na THEN 1280
1310              DISP "SOMETHING IS WRONG IN STEP I(B)."
1320              STOP
1330          R=R+Atp(Ka)
1340          NEXT I5
1350  !  Steps I(C) and II follow.  Both List A and List B are stored in K1.
1360  !  The path determined in Step I(B) is stored in proper sequence in K1.
1370  !  The next program segment ensures that the paths in K1 are sorted from
1380  !  lowest to highest cost so that the top path in List B is the next one
1390  !  to be added to List A.  Step II of the algorithm effectively becomes
1400  !  redundent since advancing K by 1 moves the top entry of List B to the
```

```
1410   !  bottom entry in List A.
1420         Bnew=R+S
1430         FOR J=I TO Jj1
1440           Kr(J)=Kh(J)
1450           NEXT J
1460         Icq=K
1470         IF Bnew<Akl(Icq) THEN 1520
1480         IF Bnew=Akl(Icq) THEN 1630
1490         IF Icq>=Np THEN 1690
1500           Icq=Icq+1
1510           GOTO 1470
1520         FOR Ik=1 TO Mn
1530           Kt(Ik)=Kl(Icq,Ik)
1540           Kl(Icq,Ik)=Kr(Ik)
1550           Kr(Ik)=Kt(Ik)
1560           NEXT Ik
1570         Akt=Akl(Icq)
1580         Akl(Icq)=Bnew
1590         Bnew=Akt
1600         IF Icq>=Np THEN 1690
1610           Icq=Icq+1
1620           GOTO 1520
1630         Id=1
1640         FOR Ik=1 TO Mn
1650           IF Kr(Ik)<>Kl(Icq,Ik) THEN Id=0
1660           NEXT Ik
1670         IF Id=1 THEN 1690
1680           GOTO 1490
1690         NEXT I
1700       J1=0
1710       FOR J=1 TO Mn
1720         IF Kl(K,J)>.0001 THEN J1=J1+1
1730         NEXT J
1740       Js(K)=J1
1750       NEXT K
```

```
1760 Finish:  DISP "TRACING OF PATH(S) COMPLETED.  RETURNING TO MAIN."
1770   LOAD "MAIN",Target2
1780   END
1790   SUB Smsp(M,J1,S)
1800   ! ************************************************************************
1810   !  This subroutine determines the shortest path from node M to node Nn
1820   !  for any acyclic network satisfying the I<J rule, using a dynamic
1830   !  programming algorithm suggested by S.E. Elmaghraby in Management
1840   !  Science 17(1): 10.
1850   ! ************************************************************************
1860   !  Variables used in subroutine SMSP not used in MAIN.
1870   !   F    -Array of dimension Nn.  F(I) is the minimum cost between node I
1880   !         and node M where I>M.
1890   !   I1   -Dummy scaler.
1900   !   Khr  -Array of dimension Mn which stores the nodes in the optimal path
1910   !         in reverse sequence starting from node J1.  For example, if M=6,
1920   !         Nn=17, J1=3, and the optimal path is 6-11-17, then Khr(3)=17,
1930   !         Khr(4)=11 and Khr(5)=6.
1940   !   Kq   -Scaler set equal to J1, the number of nodes in the root not
1950   !         including node M.
1960   !   Kx   -Dummy scaler.
1970   !   K1   -Dummy scaler.
1980   !   M    -Origin node for the least-cost spur being sought, and the
1990   !         terminal node of the current root.
2000   !   M1   -Dummy scaler.
2010   !   Op   -Array of dimension Nn containing the optimal predecessors.
2020   !         Op(I) is the node number which preceeds I in the shortest path
2030   !         from node M to node I.
2040   ! ************************************************************************
2050   OPTION BASE 1
2060   COM Na,Nn,Mn,Np,Nsv,Num,File$[6],Device$[6]
2070   COM Ix(250),Jx(250),Ic(250),Jc(250),Icr(250)
2080   COM Ak1(50),At(250),Js(50),Kh(25),INTEGER K1(50,25)
2090   DIM F(250),Khr(25),Op(250)
2100   !  Initialize variables
```

```
2110   Kq=J1
2120   MAT Khr=ZER
2130   MAT Kh=ZER
2140   M1=M+1
2150   F(M)=0
2160  !  Determine the nodes which are the optimal predecessors of each node,
2170  !  and the minimum cost between the two nodes.
2180   FOR J=M1 TO Nn
2190     Op(J)=0
2200     F(J)=1E20
2210     FOR K=1 TO Na
2220       IF Jc(K)<>J THEN 2280
2230       IF Ic(K)<M THEN 2280
2240         I=Ic(K)
2250         IF F(I)+At(K)>F(J) THEN 2280
2260           F(J)=F(I)+At(K)
2270           Op(J)=I
2280       NEXT K
2290     NEXT J
2300  !  Set-up array Khr with the optimal path in the reverse order.
2310   Kx=Nn
2320   Khr(Kq)=Nn
2330   J1=J1+1
2340   Khr(J1)=Op(Kx)
2350   Kx=Khr(J1)
2360   IF (Kx=0) OR (J1>=Mn) THEN 2400
2370     IF Kx<>M THEN 2330
2380  !  Store the nodes of the shortest path in array Kh, and set S equal to
2390  !  the length of the shortest path.
2400   FOR I=Kq TO J1
2410     Kh(I)=Khr(J1-I+Kq)
2420     NEXT I
2430   S=F(Nn)
2440   SUBEND
```

## C.2 Non-Standard BASIC Statements

The BASIC programming language implemented on the Hewlett-Packard 9845 desktop computer is an enhanced version of standard ANSII BASIC. To assist readers unfamiliar with H.-P. BASIC, a list of non-standard syntax used in LOGNAP and an explanation of its purposes follows.

Operators

| | |
|---|---|
| ^ | Exponentiate |
| & | String concatenation |

Statements

| | |
|---|---|
| COM | Dimensions and allocates memory space for the specified variables in a "common" memory area. |
| OPTION BASE 1 | Specifies that the lower bound of arrays begin with one rather than zero. The first element in array A is A(1). |
| OVERLAP | Sets the computer to an overlapped processing mode to increase I/O speed. |
| REM | Inserts non-executable remarks (comments) into a program. An exclamation mark can also be used as a comment delimiter. |
| WAIT n | Causes program execution to wait the specified number of milliseconds before it continues. |

Functions

| | |
|---|---|
| INT(expression) | Returns the integer portion of the evaluated expression. |
| LEN(string) | Returns the length of the string. |
| LIN(n) | Outputs a carriage return and the specified number of linefeeds. |
| PAGE | Outputs a formfeed. |
| RPT$(string,n) | Causes the string to be repeated the specified number of times. |
| SPA(n) | Output the specified number of blanc spaces. |
| TAB(m) | Output the next item starting in the specified position. |
| TRIM$(string) | Delete any leading or trailing blanks from the string. |
| UPC$(string) | Returns a string of all uppercase characters. |

### Array Operations

| | |
|---|---|
| MAT matrix = matrix | - Copies the value of each matrix element into a second matrix. |
| MAT matrix = matrix (expression) | - Performs an arithmetic operation on each element of a matrix with the result becoming the value of the corresponding element in the result matrix. |
| MAT matrix = ZER | - Sets all matrix elements to zero. |

### Mass Storage Operations

| | |
|---|---|
| ASSIGN file TO #n | - Open a file for accessing. |
| ASSIGN #n TO * | - Close a file. |
| CAT TO string array | - Copies the mass storage device catalogue to the specific string array. |
| CREATE file,n,m | - Establish a data file of n records of m bytes in length. |
| LOAD file | - Place a program stored in compiled form into memory. |
| READ #1,n;variables | - Positions read head to specified record number to retrieve variable values. |

# APPENDIX D

## NETWORK DEFINITION AND COSTING INPUTS

The computer output contained in this appendix summarizes data for the network shown in Figure 7 that was analyzed for this research. The report was produced by the INPUT module of the LOGNAP programs.

The first section of the output summarizes parameters which in effect identify the network's size. The second section outlines the linkages within the network in terms of each activity's initial and final nodes and a description. The final section contains the data specific to each activity which was used in the calculation of activity durations.

## BASIC NETWORK PARAMETERS

```
1. Number of activities in the network ...........133
2. Number of nodes in the network ................ 77
3. Estimated maximum number of nodes on a path ... 15
```

## ACTIVITY DATA

| ACTIVITY NUMBER | INITIAL MODE | FINAL NODE | ACTIVITY DESCRIPTION |
|---|---|---|---|
| 1 | 1 | 10 | FB Whld Shear - Forano BJ-20 |
| 2 | 1 | 11 | FB Trckd Shear - Drott 40 |
| 3 | 1 | 12 | FB Whld Multi-Shear - Koehring KFB4 |
| 4 | 1 | 13 | FB Whld Shear - Melroe Bobcat 1075 |
| 5 | 1 | 14 | FB Whld Saw - Kockums 880 |
| 6 | 1 | 15 | FB Trckd Saw - Drott 40 |
| 7 | 1 | 16 | FB Trckd Auger - Drott 40 |
| 8 | 1 | 17 | FB Whld Multi-Saw - Hydro Ax Swather |
| 9 | 10 | 20 | DUMMY |
| 10 | 11 | 20 | DUMMY |
| 11 | 12 | 20 | DUMMY |
| 12 | 13 | 20 | DUMMY |
| 13 | 14 | 20 | DUMMY |
| 14 | 15 | 20 | DUMMY |
| 15 | 16 | 20 | DUMMY |
| 16 | 17 | 20 | DUMMY |
| 17 | 1 | 30 | FELL - Man with Chain Saw |
| 18 | 1 | 31 | FELL Trckd Shear - Caterpillar D6 |
| 19 | 1 | 32 | FELL Trckd Saw - FMC & Feller-Director |
| 20 | 1 | 33 | FELL Trckd Saw - Caterpillar D6 |

## ACTIVITY DATA

| ACTIVITY NUMBER | INITIAL MODE | FINAL NODE | ACTIVITY DESCRIPTION |
|---|---|---|---|
| 21 | 30 | 40 | DUMMY |
| 22 | 31 | 40 | DUMMY |
| 23 | 32 | 40 | DUMMY |
| 24 | 33 | 40 | DUMMY |
| 25 | 40 | 50 | DEL Stumpside (loose) - Logma T-310 |
| 26 | 40 | 51 | DEL Stumpside - Drott 40 with Timmins |
| 27 | 50 | 60 | DUMMY |
| 28 | 51 | 60 | DUMMY |
| 29 | 60 | 110 | DUMMY |
| 30 | 1 | 70 | FELL & DEL - Man with Chain Saw |
| 31 | 1 | 71 | FELL & DEL - John Deere 743 |
| 32 | 70 | 80 | DUMMY |
| 33 | 71 | 80 | DUMMY |
| 34 | 1 | 90 | FELL DEL & BUNCH Whld - Timberjack TJ-30 |
| 35 | 1 | 91 | FELL DEL & BUNCH - Koehring KFB4 & Tim |
| 36 | 1 | 92 | FELL DEL & BUNCH - Drott 40 with Timmins |
| 37 | 90 | 110 | DUMMY |
| 38 | 91 | 110 | DUMMY |
| 39 | 92 | 110 | DUMMY |
| 40 | 20 | 100 | DEL Stumpside (bunched) - Logma T-310 |

## ACTIVITY DATA

| ACTIVITY NUMBER | INITIAL MODE | FINAL NODE | ACTIVITY DESCRIPTION |
|---|---|---|---|
| 41 | 20 | 101 | DEL Stumpside - GLFP/NESCO Flail |
| 42 | 20 | 102 | DEL Stumpside - Drott 40 with Timmins |
| 43 | 100 | 110 | DUMMY |
| 44 | 101 | 110 | DUMMY |
| 45 | 102 | 110 | DUMMY |
| 46 | 20 | 120 | PT (FT bunch) Whld Cable Skid - JD-540 |
| 47 | 20 | 121 | PT (FT bunch) Whld Cable Skid - JD-740 |
| 48 | 20 | 122 | PT (FT bunch) Whld Grap Skid - JD-540 |
| 49 | 20 | 123 | PT (FT bunch) Whld Grap Skid - JD-740 |
| 50 | 20 | 124 | PT (FT bunch) Whld Clam Skid - TJ 520 |
| 51 | 20 | 125 | PT (FT bunch) Whld Frwrd - Koehring KF2 |
| 52 | 20 | 126 | PT (FT bunch) Trckd Cable Skid - FMC 200 |
| 53 | 20 | 127 | PT (FT bunch) Trckd Clam Skid - FMC 200 |
| 54 | 120 | 150 | DUMMY |
| 55 | 121 | 150 | DUMMY |
| 56 | 122 | 150 | DUMMY |
| 57 | 123 | 150 | DUMMY |
| 58 | 124 | 150 | DUMMY |
| 59 | 125 | 150 | DUMMY |
| 60 | 126 | 150 | DUMMY |

## ACTIVITY DATA

| ACTIVITY NUMBER | INITIAL MODE | FINAL NODE | ACTIVITY DESCRIPTION |
|---|---|---|---|
| 61 | 127 | 150 | DUMMY |
| 62 | 40 | 130 | PT (FT loose) Whld Cable Skid - JD-540 |
| 63 | 40 | 131 | PT (FT loose) Whld Cable Skid - JD-740 |
| 64 | 40 | 132 | PT (FT loose) Whld Clam Skid - TJ 520 |
| 65 | 40 | 133 | PT (FT loose) Whld Frwrd - Koehring KF2 |
| 66 | 40 | 134 | PT (FT loose) Trckd Cable Skid - FMC 200 |
| 67 | 40 | 135 | PT (FT loose) Trckd Clam Skid - FMC 200 |
| 68 | 130 | 150 | DUMMY |
| 69 | 131 | 150 | DUMMY |
| 70 | 132 | 150 | DUMMY |
| 71 | 133 | 150 | DUMMY |
| 72 | 134 | 150 | DUMMY |
| 73 | 135 | 150 | DUMMY |
| 74 | 1 | 140 | FELL Skid Shear - TJ-520 with Head |
| 75 | 1 | 141 | FELL & Frwrd Multi-Shear - Koehring KFF |
| 76 | 1 | 142 | FELL & Frwrd Multi-Saw - Koehring KFF |
| 77 | 1 | 143 | FELL & Frwrd Saw - PAPCO Swather |
| 78 | 140 | 150 | DUMMY |
| 79 | 141 | 150 | DUMMY |
| 80 | 142 | 150 | DUMMY |

## ACTIVITY DATA

| ACTIVITY NUMBER | INITIAL MODE | FINAL NODE | ACTIVITY DESCRIPTION |
|---|---|---|---|
| 81 | 143 | 150 | DUMMY |
| 82 | 80 | 160 | PT (TL loose) Whld Cable Skid - JD-540 |
| 83 | 80 | 161 | PT (TL loose) Whld Cable Skid - JD-740 |
| 84 | 80 | 162 | PT (TL loose) Whld Grap Skid - JD-540 |
| 85 | 80 | 163 | PT (TL loose) Whld Clam Skid - TJ 520 |
| 86 | 80 | 164 | PT (TL loose) Whld Frwrd - Koehring KF2 |
| 87 | 80 | 165 | PT (TL loose) Trckd Cable Skid - FMC 200 |
| 88 | 80 | 166 | PT (TL loose) Trckd Clam Skid - FMC 200 |
| 89 | 160 | 200 | DUMMY |
| 90 | 161 | 200 | DUMMY |
| 91 | 162 | 200 | DUMMY |
| 92 | 163 | 200 | DUMMY |
| 93 | 164 | 200 | DUMMY |
| 94 | 165 | 200 | DUMMY |
| 95 | 166 | 200 | DUMMY |
| 96 | 110 | 170 | PT (TL bunch) Whld Cable Skid - JD-540 |
| 97 | 110 | 171 | PT (TL bunch) Whld Cable Skid - JD-740 |
| 98 | 110 | 172 | PT (TL bunch) Whld Grap Skid - JD-540 |
| 99 | 110 | 173 | PT (TL bunch) Whld Grap Skid - JD-740 |
| 100 | 110 | 174 | PT (TL bunch) Whld Clam Skid - TJ 520 |

## ACTIVITY DATA

| ACTIVITY NUMBER | INITIAL MODE | FINAL NODE | ACTIVITY DESCRIPTION |
|---|---|---|---|
| 101 | 110 | 175 | PT (TL bunch) Whld Frwrd - Koehring KF2 |
| 102 | 110 | 176 | PT (TL bunch) Trckd Cable Skid - FMC 200 |
| 103 | 110 | 177 | PT (TL bunch) Trckd Clam Skid - FMC 200 |
| 104 | 170 | 200 | DUMMY |
| 105 | 171 | 200 | DUMMY |
| 106 | 172 | 200 | DUMMY |
| 107 | 173 | 200 | DUMMY |
| 108 | 174 | 200 | DUMMY |
| 109 | 175 | 200 | DUMMY |
| 110 | 176 | 200 | DUMMY |
| 111 | 177 | 200 | DUMMY |
| 112 | 150 | 180 | DEL Roadside - Logma T-310 |
| 113 | 150 | 181 | DEL Roadside - Harricana |
| 114 | 150 | 182 | DEL Roadside - Koehring KBL |
| 115 | 150 | 183 | DEL Roadside - Drott 40 with Timmins |
| 116 | 150 | 184 | DEL Roadside - Hydro Ax Flail System |
| 117 | 150 | 185 | DEL Roadside - Hydro Ax 500 Flail |
| 118 | 180 | 200 | DUMMY |
| 119 | 181 | 200 | DUMMY |
| 120 | 182 | 200 | DUMMY |

## ACTIVITY DATA

| ACTIVITY NUMBER | INITIAL MODE | FINAL NODE | ACTIVITY DESCRIPTION |
|---|---|---|---|
| 121 | 183 | 200 | DUMMY |
| 122 | 184 | 185 | Loader Spreading Bunch - Tanguay 14030 |
| 123 | 185 | 200 | Man with Chain Saw |
| 124 | 1 | 190 | HARV Frwrd - Koehring KTL |
| 125 | 1 | 191 | HARV Frwrd - Koehring KFF with Timmins |
| 126 | 170 | 200 | DUMMY |
| 127 | 191 | 200 | DUMMY |
| 128 | 200 | 210 | LOAD Trckd - Caterpillar 235 |
| 129 | 210 | 220 | DUMMY |
| 130 | 220 | 230 | ST Double Load on Semi-Trailer |
| 131 | 230 | 240 | DUMMY |
| 132 | 240 | 250 | UNLOAD - Rago Wagner |
| 133 | 250 | 260 | DUMMY |

## COST VARIABLES

| ACTIVITY NUMBER | SCHEDULED HOURS | PURCHASE PRICE | HOURLY WAGE | GROSS POWER | LOAD FACTOR | HYD.C. FACTOR | REPAIR FACTOR | MTBR | OPER. EFFEC | LICENSE COST |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3840 | 160000 | 9.38 | 90 | 0.65 | 0.25 | 0.11 | 8.5 | 0.85 | 0 |
| 2 | 3840 | 165000 | 9.38 | 117 | 0.65 | 0.25 | 0.11 | 12.4 | 0.85 | 0 |
| 3 | 3840 | 250000 | 9.38 | 150 | 0.65 | 0.25 | 0.10 | 15.4 | 0.85 | 0 |
| 4 | 1920 | 75000 | 9.38 | 61 | 0.65 | 0.25 | 0.12 | 8.7 | 0.85 | 0 |
| 5 | 3840 | 185000 | 9.38 | 115 | 0.65 | 0.25 | 0.12 | 11.2 | 0.85 | 0 |
| 6 | 3840 | 170000 | 9.38 | 117 | 0.65 | 0.25 | 0.11 | 9.7 | 0.80 | 0 |
| 7 | 3840 | 170000 | 9.38 | 117 | 0.65 | 0.25 | 0.11 | 9.7 | 0.80 | 0 |
| 8 | 3840 | 225000 | 9.38 | 175 | 0.70 | 0.25 | 0.10 | 11.9 | 0.80 | 0 |
| 9 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 10 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 11 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 12 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 13 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 14 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 15 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 16 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 17 | 1920 | 0 | 10.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 18 | 3840 | 180000 | 9.38 | 104 | 0.60 | 0.20 | 0.10 | 17.0 | 0.85 | 0 |
| 19 | 3840 | 175000 | 7.38 | 147 | 0.65 | 0.25 | 0.11 | 12.4 | 0.85 | 0 |
| 20 | 3840 | 185000 | 9.38 | 104 | 0.65 | 0.25 | 0.10 | 15.6 | 0.85 | 0 |

## COST VARIABLES

| ACTIVITY NUMBER | SCHEDULED HOURS | PURCHASE PRICE | HOURLY WAGE | GROSS POWER | LOAD FACTOR | HYD.C. FACTOR | REPAIR FACTOR | MTBR | OPER. EFFEC | LICENSE COST |
|---|---|---|---|---|---|---|---|---|---|---|
| 21 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 22 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 23 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 24 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 25 | 3840 | 210000 | 9.38 | 153 | 0.70 | 0.40 | 0.11 | 7.9 | 0.90 | 0 |
| 26 | 3840 | 160000 | 9.38 | 117 | 0.70 | 0.25 | 0.10 | 7.9 | 0.90 | 0 |
| 27 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 28 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 29 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 30 | 1920 | 0 | 10.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 31 | 3840 | 215000 | 9.66 | 113 | 0.65 | 0.40 | 0.12 | 11.6 | 0.81 | 0 |
| 32 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 33 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 34 | 3840 | 180000 | 9.66 | 69 | 0.70 | 0.40 | 0.12 | 12.0 | 0.85 | 0 |
| 35 | 3840 | 250000 | 9.66 | 172 | 0.70 | 0.40 | 0.10 | 12.7 | 0.85 | 0 |
| 36 | 3840 | 170000 | 9.66 | 117 | 0.70 | 0.40 | 0.11 | 7.9 | 0.85 | 0 |
| 37 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 38 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 39 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 40 | 3840 | 210000 | 9.30 | 153 | 0.70 | 0.40 | 0.11 | 7.9 | 0.90 | 0 |

## COST VARIABLES

| ACTIVITY NUMBER | SCHEDULED HOURS | PURCHASE PRICE | HOURLY WAGE | GROSS POWER | LOAD FACTOR | HYD.C. FACTOR | REPAIR FACTOR | MTBR | OPER. EFFEC | LICENSE COST |
|---|---|---|---|---|---|---|---|---|---|---|
| 41 | 3840 | 200000 | 9.38 | 113 | 0.65 | 0.25 | 0.10 | 9.0 | 0.80 | 0 |
| 42 | 3840 | 170000 | 9.38 | 117 | 0.70 | 0.25 | 0.11 | 8.5 | 0.85 | 0 |
| 43 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 44 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 45 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 46 | 1920 | 48000 | 9.15 | 67 | 0.65 | 0.15 | 0.08 | 23.5 | 0.95 | 0 |
| 47 | 1920 | 65000 | 9.15 | 108 | 0.65 | 0.15 | 0.08 | 22.7 | 0.95 | 0 |
| 48 | 1920 | 50000 | 9.15 | 67 | 0.65 | 0.20 | 0.09 | 22.6 | 0.90 | 0 |
| 49 | 1920 | 70000 | 9.15 | 108 | 0.65 | 0.20 | 0.09 | 20.8 | 0.90 | 0 |
| 50 | 3840 | 175000 | 9.15 | 138 | 0.70 | 0.20 | 0.10 | 16.3 | 0.93 | 0 |
| 51 | 3840 | 325000 | 9.38 | 257 | 0.70 | 0.25 | 0.10 | 11.8 | 0.90 | 0 |
| 52 | 1920 | 165000 | 9.15 | 147 | 0.65 | 0.15 | 0.10 | 19.1 | 0.95 | 0 |
| 53 | 1920 | 175000 | 9.38 | 147 | 0.70 | 0.20 | 0.10 | 15.4 | 0.93 | 0 |
| 54 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 55 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 56 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 57 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 58 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 59 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 60 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |

## COST VARIABLES

| ACTIVITY NUMBER | SCHEDULED HOURS | PURCHASE PRICE | HOURLY WAGE | GROSS POWER | LOAD FACTOR | HYD.C. FACTOR | REPAIR FACTOR | MTBR | OPER. EFFEC | LICENSE COST |
|---|---|---|---|---|---|---|---|---|---|---|
| 61 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 62 | 1920 | 48000 | 9.15 | 67 | 0.65 | 0.15 | 0.08 | 23.5 | 0.95 | 0 |
| 63 | 1920 | 65000 | 9.15 | 108 | 0.65 | 0.15 | 0.08 | 22.7 | 0.95 | 0 |
| 64 | 3840 | 175000 | 9.38 | 138 | 0.70 | 0.20 | 0.10 | 16.3 | 0.93 | 0 |
| 65 | 3840 | 325000 | 9.38 | 257 | 0.70 | 0.25 | 0.10 | 11.8 | 0.90 | 0 |
| 66 | 1920 | 165000 | 9.15 | 147 | 0.65 | 0.15 | 0.10 | 19.1 | 0.95 | 0 |
| 67 | 1920 | 175000 | 9.38 | 147 | 0.70 | 0.20 | 0.10 | 15.4 | 0.93 | 0 |
| 68 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 69 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 70 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 71 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 72 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 73 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 74 | 3840 | 185000 | 9.66 | 138 | 0.70 | 0.20 | 0.11 | 19.3 | 0.85 | 0 |
| 75 | 3840 | 325000 | 9.66 | 257 | 0.70 | 0.25 | 0.10 | 11.8 | 0.70 | 0 |
| 76 | 3840 | 325000 | 9.66 | 257 | 0.70 | 0.25 | 0.10 | 10.6 | 0.85 | 0 |
| 77 | 1920 | 225000 | 19.32 | 200 | 0.75 | 0.25 | 0.10 | 12.5 | 0.85 | 0 |
| 78 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 79 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 80 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |

## COST VARIABLES

| ACTIVITY NUMBER | SCHEDULED HOURS | PURCHASE PRICE | HOURLY WAGE | GROSS POWER | LOAD FACTOR | HYD.C. FACTOR | REPAIR FACTOR | MTBR | OPER. EFFEC | LICENSE COST |
|---|---|---|---|---|---|---|---|---|---|---|
| 81 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 82 | 1920 | 48000 | 9.15 | 67 | 0.65 | 0.15 | 0.08 | 23.5 | 0.95 | 0 |
| 83 | 1920 | 65000 | 9.15 | 108 | 0.65 | 0.15 | 0.08 | 22.7 | 0.95 | 0 |
| 84 | 1920 | 50000 | 9.15 | 67 | 0.65 | 0.20 | 0.09 | 22.6 | 0.93 | 0 |
| 85 | 3840 | 175000 | 9.15 | 138 | 0.70 | 0.25 | 0.10 | 16.3 | 0.93 | 0 |
| 86 | 3840 | 325000 | 9.38 | 257 | 0.70 | 0.25 | 0.10 | 10.2 | 0.90 | 0 |
| 87 | 1920 | 165000 | 9.15 | 147 | 0.65 | 0.15 | 0.10 | 19.1 | 0.95 | 0 |
| 88 | 1920 | 175000 | 9.15 | 147 | 0.70 | 0.20 | 0.10 | 15.4 | 0.93 | 0 |
| 89 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 90 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 91 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 92 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 93 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 94 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 95 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 96 | 1920 | 48000 | 9.15 | 67 | 0.65 | 0.15 | 0.08 | 23.5 | 0.95 | 0 |
| 97 | 1920 | 65000 | 9.15 | 108 | 0.65 | 0.15 | 0.08 | 22.7 | 0.95 | 0 |
| 98 | 1920 | 50000 | 9.15 | 67 | 0.65 | 0.20 | 0.09 | 22.6 | 0.90 | 0 |
| 99 | 1920 | 70000 | 9.15 | 108 | 0.65 | 0.20 | 0.09 | 20.8 | 0.90 | 0 |
| 100 | 3840 | 175000 | 9.15 | 138 | 0.70 | 0.25 | 0.10 | 16.3 | 0.93 | 0 |

## COST VARIABLES

| ACTIVITY NUMBER | SCHEDULED HOURS | PURCHASE PRICE | HOURLY WAGE | GROSS POWER | LOAD FACTOR | HYD.C. FACTOR | REPAIR FACTOR | MTBR | OPER. EFFEC | LICENSE COST |
|---|---|---|---|---|---|---|---|---|---|---|
| 101 | 3840 | 325000 | 9.38 | 257 | 0.70 | 0.25 | 0.10 | 11.8 | 0.90 | 0 |
| 102 | 1920 | 165000 | 9.15 | 147 | 0.65 | 0.15 | 0.10 | 19.1 | 0.95 | 0 |
| 103 | 1920 | 175000 | 9.15 | 147 | 0.70 | 0.20 | 0.10 | 15.4 | 0.93 | 0 |
| 104 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 105 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 106 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 107 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 108 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 109 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 110 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 111 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 112 | 3840 | 210000 | 9.38 | 153 | 0.70 | 0.40 | 0.10 | 7.9 | 0.90 | 0 |
| 113 | 3840 | 170000 | 9.38 | 145 | 0.70 | 0.40 | 0.11 | 6.7 | 0.90 | 0 |
| 114 | 3840 | 325000 | 9.66 | 257 | 0.75 | 0.40 | 0.12 | 8.9 | 0.90 | 0 |
| 115 | 3840 | 160000 | 9.38 | 117 | 0.70 | 0.25 | 0.10 | 9.4 | 0.70 | 0 |
| 116 | 3840 | 110000 | 9.38 | 68 | 0.70 | 0.25 | 0.11 | 14.7 | 0.80 | 0 |
| 117 | 3840 | 110000 | 9.38 | 68 | 0.70 | 0.25 | 0.11 | 14.7 | 0.70 | 0 |
| 118 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 119 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 120 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |

## COST VARIABLES

| ACTIVITY NUMBER | SCHEDULED HOURS | PURCHASE PRICE | HOURLY WAGE | GROSS POWER | LOAD FACTOR | HYD.C. FACTOR | REPAIR FACTOR | MTBR | OPER. EFFEC | LICENSE COST |
|---|---|---|---|---|---|---|---|---|---|---|
| 121 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 122 | 3840 | 180000 | 9.29 | 123 | 0.70 | 0.25 | 0.08 | 12.3 | 0.70 | 0 |
| 123 | 1920 | 0 | 10.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 124 | 3840 | 340000 | 9.66 | 257 | 0.70 | 0.40 | 0.12 | 8.4 | 0.90 | 0 |
| 125 | 3840 | 325000 | 9.66 | 257 | 0.70 | 0.40 | 0.11 | 10.6 | 0.90 | 0 |
| 126 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 127 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 128 | 3840 | 235000 | 9.29 | 145 | 0.70 | 0.25 | 0.08 | 13.9 | 0.80 | 0 |
| 129 | 0 | 0 | 0.00 | 0 | 0.70 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 130 | 3840 | 80000 | 9.22 | 283 | 0.75 | 0.10 | 0.13 | 15.7 | 0.80 | 1700 |
| 131 | 0 | 0 | 0.00 | 0 | 0.70 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |
| 132 | 8400 | 360000 | 9.29 | 250 | 0.00 | 0.40 | 0.11 | 9.5 | 0.70 | 0 |
| 133 | 0 | 0 | 0.00 | 0 | 0.00 | 0.00 | 0.00 | 0.0 | 0.00 | 0 |

# APPENDIX E

# COMPUTER RUN RESULTS

Computer output summaries of runs made using the LOGNAP computer programs on the network summarized in Appendix D follow. Individual systems of equipment were ranked in ascending order of total cost per cubic meter of tree-length wood unloaded at the mill.

The appendix is sectioned as follows:

E.1. Primary Computer Run
E.2. Sensitivity Analysis - Fuel Price
E.3. Sensitivity Analysis - Average Tree Size and Stand Volume.

Note that a complete computer output of 50 shortest paths is included for the primary computer run. In the sections related to sensitivity analysis, only summaries of the first 25 least-cost paths are included.

The node numbers defining the shortest paths refer to those shown in Figure 7.

## E.1. Primary Computer Run

Results of the main computer run are contained in this section. Note that these results were also used as the standard conditions in all sensitivity analysis.

```
                    STANDARD VARIABLES FOR RUN 1

ECONOMIC VARIABLES:

  1.  Interest Rate (%) ................................ 12.00
  2.  Fuel Price ($/liter) .............................. 0.22
  3.  Repair Time In-Shift (% of total repair time) ..... 85.00
  4.  Fringe Benefit Factor (% of hourly wage) .......... 35.00
  5.  Insurance Rate Factor (% of unrecovered value) ....  3.00
  6.  Rate of Lost Utility (%) .......................... 30.00

OPERATING VARIABLES:

  1.  Species (Pj=1,Sb=2,Sw=3,Fb=4) .....................  2.00
  2.  Average Tree Size (DBH in cm) ..................... 18.00
  3.  Stand Volume (m^3/hectare) ........................100.00
  4.  Average Primary Transport Distance (meters) .......150.00
  5.  Hauling Distance - Road Class 1 (km) .............. 96.00
  6.  Hauling Distance - Road Class 2 (km) .............. 16.00
  7.  Hauling Distance - Road Class 3 (km) ..............  3.00
  8.  Average Slope (%) .................................  0.00
```

```
                          ACTIVITY DURATIONS FOR RUN 1

 ACTIVITY   HOURLY    HOURLY      WOOD                 ACTIVITY DESCRIPTION
  NUMBER     COST   PRODUCTION    COST
           ($/PMH)  (m^3/PMH)   ($/m^3)
--------------------------------------------------------------------------------

     1      55.46      17.14      3.23    FB Whld Shear - Forano BJ-20
     2      55.84      21.11      2.65    FB Trckd Shear - Drott 40
     3      69.03      22.02      3.14    FB Whld Multi-Shear - Koehring KFB4
     4      44.94      18.91      2.38    FB Whld Shear - Melroe Bobcat 1075
     5      61.57      22.43      2.75    FB Whld Saw - Kockums 880

     6      59.84      15.96      3.75    FB Trckd Saw - Drott 40
     7      59.84      15.96      3.75    FB Trckd Auger - Drott 40
     8      69.53      18.62      3.73    FB Whld Multi-Saw - Hydro Ax Swather
     9       0.00       0.00      0.00    DUMMY
    10       0.00       0.00      0.00    DUMMY

    11       0.00       0.00      0.00    DUMMY
    12       0.00       0.00      0.00    DUMMY
    13       0.00       0.00      0.00    DUMMY
    14       0.00       0.00      0.00    DUMMY
    15       0.00       0.00      0.00    DUMMY

    16       0.00       0.00      0.00    DUMMY
    17      13.50       7.50      1.80    FELL - Man with Chain Saw
    18      54.86      23.02      2.38    FELL Trckd Shear - Caterpillar D6
    19      58.76      11.74      5.00    FELL Trckd Saw - FMC & Feller-Director
    20      56.37      22.19      2.54    FELL Trckd Saw - Caterpillar D6
```

## ACTIVITY DURATIONS FOR RUN 1

| ACTIVITY NUMBER | HOURLY COST ($/PMH) | HOURLY PRODUCTION (m^3/PMH) | WOOD COST ($/m^3) | ACTIVITY DESCRIPTION |
|---|---|---|---|---|
| 21 | 0.00 | 0.00 | 0.00 | DUMMY |
| 22 | 0.00 | 0.00 | 0.00 | DUMMY |
| 23 | 0.00 | 0.00 | 0.00 | DUMMY |
| 24 | 0.00 | 0.00 | 0.00 | DUMMY |
| 25 | 66.39 | 13.97 | 4.75 | DEL Stumpside (loose) - Logma T-310 |
| 26 | 53.64 | 16.55 | 3.24 | DEL Stumpside - Drott 40 with Timmins |
| 27 | 0.00 | 0.00 | 0.00 | DUMMY |
| 28 | 0.00 | 0.00 | 0.00 | DUMMY |
| 29 | 0.00 | 0.00 | 0.00 | DUMMY |
| 30 | 13.50 | 3.16 | 4.27 | FELL & DEL - Man with Chain Saw |
| 31 | 70.08 | 13.42 | 5.22 | FELL & DEL - John Deere 743 |
| 32 | 0.00 | 0.00 | 0.00 | DUMMY |
| 33 | 0.00 | 0.00 | 0.00 | DUMMY |
| 34 | 59.83 | 11.19 | 5.35 | FELL DEL & BUNCH Whld - Timberjack TJ-30 |
| 35 | 72.51 | 13.32 | 5.45 | FELL DEL & BUNCH - Koehring KFB4 & Tim |
| 36 | 60.27 | 11.87 | 5.08 | FELL DEL & BUNCH - Drott 40 with Timmins |
| 37 | 0.00 | 0.00 | 0.00 | DUMMY |
| 38 | 0.00 | 0.00 | 0.00 | DUMMY |
| 39 | 0.00 | 0.00 | 0.00 | DUMMY |
| 40 | 66.20 | 18.04 | 3.67 | DEL Stumpside (bunched) - Logma T-310 |

```
                    ACTIVITY DURATIONS FOR RUN 1

ACTIVITY   HOURLY     HOURLY     WOOD               ACTIVITY DESCRIPTION
 NUMBER     COST    PRODUCTION   COST
          ($/PMH)   (m^3/PMH)  ($/m^3)
-----------------------------------------------------------------------------------

   41       63.64      22.81      2.79   DEL Stumpside - GLFP/NESCO Flail
   42       58.63      25.45      2.30   DEL Stumpside - Drott 40 with Timmins
   43        0.00       0.00      0.00   DUMMY
   44        0.00       0.00      0.00   DUMMY
   45        0.00       0.00      0.00   DUMMY

   46       30.00       7.69      3.90   PT (FT bunch) Whld Cable Skid - JD-540
   47       34.84       9.94      3.51   PT (FT bunch) Whld Cable Skid - JD-740
   48       32.41      20.85      1.55   PT (FT bunch) Whld Grap Skid - JD-540
   49       38.31      31.32      1.22   PT (FT bunch) Whld Grap Skid - JD-740
   50       52.69      25.68      2.05   PT (FT bunch) Whld Clam Skid - TJ 520

   51       84.98      20.91      4.06   PT (FT bunch) Whld Frwrd - Koehring KF2
   52       59.68      16.68      3.58   PT (FT bunch) Trckd Cable Skid - FMC 200
   53       64.48      20.07      3.21   PT (FT bunch) Trckd Clam Skid - FMC 200
   54        0.00       0.00      0.00   DUMMY
   55        0.00       0.00      0.00   DUMMY

   56        0.00       0.00      0.00   DUMMY
   57        0.00       0.00      0.00   DUMMY
   58        0.00       0.00      0.00   DUMMY
   59        0.00       0.00      0.00   DUMMY
   60        0.00       0.00      0.00   DUMMY
```

```
                    ACTIVITY DURATIONS FOR RUN 1

ACTIVITY   HOURLY    HOURLY     WOOD                 ACTIVITY DESCRIPTION
 NUMBER     COST   PRODUCTION   COST
          ($/PMH)  (m^3/PMH)  ($/m^3)
---------------------------------------------------------------------------------

   61        0.00       0.00     0.00    DUMMY
   62       30.00       6.98     4.30    PT (FT loose) Whld Cable Skid - JD-540
   63       34.84       8.96     3.89    PT (FT loose) Whld Cable Skid - JD-740
   64       53.17      20.50     2.59    PT (FT loose) Whld Clam Skid - TJ 520
   65       84.98      14.34     5.93    PT (FT loose) Whld Frwrd - Koehring KF2

   66       59.68      20.27     2.94    PT (FT loose) Trckd Cable Skid - FMC 200
   67       64.48      17.28     3.73    PT (FT loose) Trckd Clam Skid - FMC 200
   68        0.00       0.00     0.00    DUMMY
   69        0.00       0.00     0.00    DUMMY
   70        0.00       0.00     0.00    DUMMY

   71        0.00       0.00     0.00    DUMMY
   72        0.00       0.00     0.00    DUMMY
   73        0.00       0.00     0.00    DUMMY
   74       59.77      13.26     4.51    FELL Skid Shear - TJ-520 with Head
   75       85.61      18.22     4.70    FELL & Frwrd Multi-Shear - Koehring KFF

   76       88.66      17.55     5.05    FELL & Frwrd Multi-Saw - Koehring KFF
   77      107.29      61.20     1.75    FELL & Frwrd Saw - PAPCO Swather
   78        0.00       0.00     0.00    DUMMY
   79        0.00       0.00     0.00    DUMMY
   80        0.00       0.00     0.00    DUMMY
```

```
                    ACTIVITY DURATIONS FOR RUN 1

ACTIVITY   HOURLY     HOURLY      WOOD              ACTIVITY DESCRIPTION
 NUMBER     COST    PRODUCTION    COST
          ($/PMH)  (m^3/PMH)   ($/m^3)
-----------------------------------------------------------------------------

   81        0.00       0.00      0.00     DUMMY
   82       30.00       9.73      3.08     PT (TL loose) Whld Cable Skid - JD-540
   83       34.84      11.58      3.01     PT (TL loose) Whld Cable Skid - JD-740
   84       31.58      21.61      1.46     PT (TL loose) Whld Grap Skid - JD-540
   85       52.92      24.76      2.14     PT (TL loose) Whld Clam Skid - TJ 520

   86       85.68      14.97      5.72     PT (TL loose) Whld Frwrd - Koehring KF2
   87       59.68      22.74      2.62     PT (TL loose) Trckd Cable Skid - FMC 200
   88       64.00      24.39      2.62     PT (TL loose) Trckd Clam Skid - FMC 200
   89        0.00       0.00      0.00     DUMMY
   90        0.00       0.00      0.00     DUMMY

   91        0.00       0.00      0.00     DUMMY
   92        0.00       0.00      0.00     DUMMY
   93        0.00       0.00      0.00     DUMMY
   94        0.00       0.00      0.00     DUMMY
   95        0.00       0.00      0.00     DUMMY

   96       30.00       9.95      3.01     PT (TL bunch) Whld Cable Skid - JD-540
   97       34.84      11.73      2.97     PT (TL bunch) Whld Cable Skid - JD-740
   98       32.41      27.95      1.16     PT (TL bunch) Whld Grap Skid - JD-540
   99       38.31      41.60      0.92     PT (TL bunch) Whld Grap Skid - JD-740
  100       52.92      28.03      1.89     PT (TL bunch) Whld Clam Skid - TJ 520
```

```
                      ACTIVITY DURATIONS FOR RUN 1

ACTIVITY   HOURLY     HOURLY      WOOD                  ACTIVITY DESCRIPTION
 NUMBER     COST    PRODUCTION    COST
          ($/PMH)   (m^3/PMH)   ($/m^3)
-------------------------------------------------------------------------------------

  101       84.98      22.29      3.81    PT (TL bunch) Whld Frwrd - Koehring KF2
  102       59.68      24.76      2.41    PT (TL bunch) Trckd Cable Skid - FMC 200
  103       64.00      28.34      2.26    PT (TL bunch) Trckd Clam Skid - FMC 200
  104        0.00       0.00      0.00    DUMMY
  105        0.00       0.00      0.00    DUMMY

  106        0.00       0.00      0.00    DUMMY
  107        0.00       0.00      0.00    DUMMY
  108        0.00       0.00      0.00    DUMMY
  109        0.00       0.00      0.00    DUMMY
  110        0.00       0.00      0.00    DUMMY

  111        0.00       0.00      0.00    DUMMY
  112       64.29      23.04      2.79    DEL Roadside - Logma T-310
  113       59.77      20.28      2.95    DEL Roadside - Harricana
  114       95.65      18.25      5.24    DEL Roadside - Koehring KBL
  115       52.86      33.17      1.59    DEL Roadside - Drott 40 with Timmins

  116       45.70      50.69      0.90    DEL Roadside - Hydro Ax Flail System
  117       50.11      45.63      1.10    DEL Roadside - Hydro Ax 500 Flail
  118        0.00       0.00      0.00    DUMMY
  119        0.00       0.00      0.00    DUMMY
  120        0.00       0.00      0.00    DUMMY
```

```
                         ACTIVITY DURATIONS FOR RUN 1

ACTIVITY   HOURLY    HOURLY     WOOD                 ACTIVITY DESCRIPTION
 NUMBER     COST   PRODUCTION   COST
          ($/PMH)  (m^3/PMH)  ($/m^3)
-----------------------------------------------------------------------------------

   121      0.00      0.00      0.00    DUMMY
   122     60.85     45.63      1.33    Loader Spreading Bunch - Tanguay 14030
   123     13.50     60.83      0.22    Man with Chain Saw
   124     98.00     10.91      8.98    HARV Frwrd - Koehring KTL
   125     90.61     13.10      6.92    HARV Frwrd - Koehring KFF with Timmins

   126      0.00      0.00      0.00    DUMMY
   127      0.00      0.00      0.00    DUMMY
   128     64.52     57.39      1.12    LOAD Trckd - Caterpillar 235
   129      0.00      0.00      0.00    DUMMY
   130     49.89     20.58      2.42    ST Double Load on Semi-Trailer

   131      0.00      0.00      0.00    DUMMY
   132     80.98    927.71      0.09    UNLOAD - Rago Wagner
   133      0.00      0.00      0.00    DUMMY
```

```
                         SHORTEST PATHS THROUGH NETWORK
                                   RUN # 1

 PATH      TOTAL                          NODES ON PATH
NUMBER     COST
----------------------------------------------------------------------------------------

   1        6.71       1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   2        6.98       1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   3        7.85       1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
   4        8.18       1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
   5        8.34       1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,

   6        8.56       1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   7        8.82       1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   8        8.83       1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   9        8.89       1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  10        8.92       1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  11        9.10       1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  12        9.16       1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  13        9.16       1,  13,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  14        9.20       1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  15        9.24       1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,

  16        9.26       1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  17        9.31       1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  18        9.35       1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  19        9.36       1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,
  20        9.39       1,  13,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  21        9.41       1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  22        9.43       1,  11,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  23        9.46       1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  24        9.48       1,  13,  20, 102, 110, 172, 200, 210, 220, 230, 240, 250, 260,
  25        9.51       1,  11,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
                    SHORTEST PATHS THROUGH NETWORK
                               RUN # 1

 PATH      TOTAL                         NODES ON PATH
NUMBER     COST
-------------------------------------------------------------------------------------

  26        9.53      1,  14,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  27        9.59      1,  12,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  28        9.60      1,  30,  40,  51,  60, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  29        9.61      1,  14,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  30        9.62      1,  30,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  31        9.64      1,  92, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  32        9.65      1,  12,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  33        9.65      1,  11,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  34        9.66      1, 141, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  35        9.66      1,  13,  20, 124, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  36        9.69      1,  10,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  37        9.69      1,  13,  20, 123, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  38        9.70      1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  39        9.72      1,  13,  20, 101, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  40        9.74      1, 140, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  41        9.74      1,  11,  20, 102, 110, 172, 200, 210, 220, 230, 240, 250, 260,
  42        9.75      1,  10,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  43        9.75      1,  14,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  44        9.84      1,  30,  40,  51,  60, 110, 172, 200, 210, 220, 230, 240, 250, 260,
  45        9.84      1,  14,  20, 102, 110, 172, 200, 210, 220, 230, 240, 250, 260,

  46        9.87      1,  92, 110, 172, 200, 210, 220, 230, 240, 250, 260,
  47        9.91      1,  90, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  48        9.91      1,  17,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  49        9.92      1,  12,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  50        9.93      1,  11,  20, 124, 150, 183, 200, 210, 220, 230, 240, 250, 260,
```

## E.2. Sensitivity Analysis - Energy Prices

Results of the computer runs made to determine the sensitivity of forest harvesting systems to energy price variations are summarized in this section. Table E.1. shows the fuel price assumed for each run. Other standard variables were held constant at values used in the primary run.

Table E.1. Fuel Prices Assumed in the Analysis of System Selection Sensitivity to Energy Prices.

| Fuel Price ($/L) | % of Standard Price | Computer Run Number |
|---|---|---|
| 0.165 | 75% | RUN 1 |
| 0.22 | 100% | PRIMARY RUN |
| 0.775 | 125% | RUN 2 |
| 0.33 | 150% | RUN 3 |
| 0.385 | 175% | RUN 4 |
| 0.44 | 200% | RUN 5 |

```
                        SHORTEST PATHS THROUGH NETWORK
                                   RUN # 1

 PATH       TOTAL                          NODES ON PATH
NUMBER      COST
------------------------------------------------------------------------------------------------------

   1         5.90      1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   2         6.11      1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   3         6.89      1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
   4         7.16      1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
   5         7.29      1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,

   6         7.51      1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   7         7.73      1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   8         7.75      1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   9         7.80      1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  10         7.84      1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  11         7.96      1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  12         8.02      1,  13,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  13         8.04      1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  14         8.05      1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  15         8.08      1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,

  16         8.13      1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  17         8.18      1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  18         8.24      1,  13,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  19         8.25      1,  11,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  20         8.27      1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  21         8.29      1,  13,  20, 102, 110, 172, 200, 210, 220, 230, 240, 250, 260,
  22         8.31      1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  23         8.32      1,  11,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  24         8.34      1,  14,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  25         8.39      1,  12,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
                          SHORTEST PATHS THROUGH NETWORK
                                     RUN # 2

 PATH      TOTAL                                 NODES ON PATH
NUMBER     COST
------------------------------------------------------------------------------------------------

   1       7.52     1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   2       7.86     1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   3       8.80     1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
   4       9.20     1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
   5       9.38     1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,

   6       9.60     1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   7       9.90     1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   8       9.93     1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   9       9.97     1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  10      10.00     1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,

  11      10.01     1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  12      10.24     1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  13      10.27     1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  14      10.27     1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  15      10.31     1,  13,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  16      10.35     1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  17      10.39     1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  18      10.39     1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  19      10.45     1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  20      10.53     1,  13,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  21      10.56     1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  22      10.57     1,  30,  40,  51,  60, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  23      10.60     1,  30,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  24      10.61     1,  11,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  25      10.62     1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
                     SHORTEST PATHS THROUGH NETWORK
                                RUN # 3

 PATH      TOTAL                         NODES ON PATH
NUMBER     COST
----------------------------------------------------------------------------------------------

   1        8.33      1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   2        8.73      1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   3        9.75      1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
   4       10.22      1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
   5       10.42      1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,

   6       10.64      1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,
   7       10.64      1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   8       10.98      1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   9       11.04      1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  10       11.05      1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  11       11.10      1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  12       11.18      1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  13       11.37      1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  14       11.39      1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  15       11.45      1,  13,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  16       11.48      1,  70,  80, 163, 200, 210, 220, 230, 240, 250, 260,
  17       11.50      1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  18       11.51      1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  19       11.55      1,  30,  40,  51,  60, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  20       11.55      1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,

  21       11.58      1,  30,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  22       11.59      1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  23       11.62      1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  24       11.68      1,  13,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  25       11.71      1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
                    SHORTEST PATHS THROUGH NETWORK
                               RUN # 4

 PATH      TOTAL                         NODES ON PATH
NUMBER     COST
-----------------------------------------------------------------------------------------------

  1        9.14       1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  2        9.60       1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  3       10.71       1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  4       11.25       1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
  5       11.28       1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,

  6       11.46       1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,
  7       11.68       1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  8       12.05       1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  9       12.10       1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 10       12.14       1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,

 11       12.14       1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 12       12.19       1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 13       12.20       1,  70,  80, 163, 200, 210, 220, 230, 240, 250, 260,
 14       12.51       1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 15       12.51       1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,

 16       12.52       1,  30,  40,  51,  60, 110, 173, 200, 210, 220, 230, 240, 250, 260,
 17       12.56       1,  30,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 18       12.58       1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 19       12.60       1,  13,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 20       12.64       1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,

 21       12.65       1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 22       12.70       1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
 23       12.72       1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 24       12.82       1,  13,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 25       12.85       1,  30,  40,  51,  60, 110, 172, 200, 210, 220, 230, 240, 250, 260,
                    SHORTEST PATHS THROUGH NETWORK
                               RUN # 5

 PATH      TOTAL                            NODES ON PATH
NUMBER     COST
------------------------------------------------------------------------------------------------

  1         9.95     1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  2        10.47     1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  3        11.66     1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  4        11.91     1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,
  5        12.27     1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,

  6        12.51     1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,
  7        12.72     1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  8        12.93     1,  70,  80, 163, 200, 210, 220, 230, 240, 250, 260,
  9        13.01     1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 10        13.13     1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

 11        13.22     1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 12        13.24     1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 13        13.28     1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 14        13.50     1,  30,  40,  51,  60, 110, 173, 200, 210, 220, 230, 240, 250, 260,
 15        13.53     1,  30,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,

 16        13.54     1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 17        13.62     1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 18        13.65     1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 19        13.66     1,  70,  80, 166, 200, 210, 220, 230, 240, 250, 260,
 20        13.66     1,  70,  80, 165, 200, 210, 220, 230, 240, 250, 260,

 21        13.74     1,  13,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 22        13.77     1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 23        13.80     1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 24        13.85     1,  30,  40,  51,  60, 110, 172, 200, 210, 220, 230, 240, 250, 260,
 25        13.86     1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
```

## E.3. Sensitivity Analysis - Average Tree Size and Stand Volume

Results of the computer runs made to determine the sensitivity of forest harvesting systems to variations in average tree size and stand volume are summarized in this section. Table E.2. shows the variable values assumed for each run. Other standard variables were held constant at values used in the primary run.

Table E.2. Average Tree Sizes and Stand Volumes Assumed in the Analysis of Optimal Operating Zones.

| TREE DBH (cm) | STAND VOLUME ($m^3$/ha) | | | |
|---|---|---|---|---|
| | 60 | 100 | 140 | 180 |
| 12 | RUN 1 | RUN 2 | RUN 3 | RUN 4 |
| 18 | RUN 5 | PRIMARY | RUN 6 | RUN 7 |
| 24 | RUN 8 | RUN 9 | RUN 10 | RUN 11 |
| 30 | RUN 12 | RUN 13 | RUN 14 | RUN 15 |

```
                         SHORTEST PATHS THROUGH NETWORK
                                   RUN # 1

 PATH       TOTAL                          NODES ON PATH
NUMBER      COST
------------------------------------------------------------------------------------

   1        10.78      1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   2        10.79      1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   3        11.19      1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,
   4        11.50      1,  70,  80, 163, 200, 210, 220, 230, 240, 250, 260,
   5        11.88      1,  70,  80, 165, 200, 210, 220, 230, 240, 250, 260,

   6        12.84      1, 141, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   7        12.85      1, 141, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   8        12.98      1,  70,  80, 166, 200, 210, 220, 230, 240, 250, 260,
   9        13.01      1,  12,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  10        13.02      1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  11        13.21      1, 142, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  12        13.22      1, 142, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  13        13.33      1,  30,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  14        13.34      1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  15        13.57      1,  12,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  16        13.58      1,  12,  20, 124, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  17        13.58      1,  12,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  18        13.59      1,  12,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  19        13.93      1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  20        13.94      1,  70,  80, 160, 200, 210, 220, 230, 240, 250, 260,

  21        14.14      1,  70,  80, 161, 200, 210, 220, 230, 240, 250, 260,
  22        14.14      1,  17,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  23        14.15      1,  17,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  24        14.50      1,  12,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  25        14.65      1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
                  SHORTEST PATHS THROUGH NETWORK
                             RUN # 2

 PATH      TOTAL                       NODES ON PATH
NUMBER     COST
-----------------------------------------------------------------------------------

  1         9.61        1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  2         9.62        1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  3        11.19        1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,
  4        11.50        1,  70,  80, 163, 200, 210, 220, 230, 240, 250, 260,
  5        11.88        1,  70,  80, 165, 200, 210, 220, 230, 240, 250, 260,

  6        12.76        1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  7        12.84        1, 141, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  8        12.85        1, 141, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  9        12.98        1,  70,  80, 166, 200, 210, 220, 230, 240, 250, 260,
 10        13.01        1,  12,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,

 11        13.02        1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 12        13.21        1, 142, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 13        13.22        1, 142, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 14        13.33        1,  30,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 15        13.34        1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,

 16        13.48        1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
 17        13.57        1,  12,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 18        13.58        1,  12,  20, 124, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 19        13.58        1,  12,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 20        13.59        1,  12,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,

 21        13.94        1,  70,  80, 160, 200, 210, 220, 230, 240, 250, 260,
 22        14.11        1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,
 23        14.14        1,  70,  80, 161, 200, 210, 220, 230, 240, 250, 260,
 24        14.14        1,  17,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 25        14.15        1,  17,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
                        SHORTEST PATHS THROUGH NETWORK
                                    RUN # 3

PATH       TOTAL                           NODES ON PATH
NUMBER     COST
------------------------------------------------------------------------------------------

  1         9.11      1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  2         9.12      1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  3        11.19      1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,
  4        11.50      1,  70,  80, 163, 200, 210, 220, 230, 240, 250, 260,
  5        11.88      1,  70,  80, 165, 200, 210, 220, 230, 240, 250, 260,

  6        12.26      1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  7        12.84      1, 141, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  8        12.85      1, 141, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  9        12.98      1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
 10        12.98      1,  70,  80, 166, 200, 210, 220, 230, 240, 250, 260,

 11        13.01      1,  12,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 12        13.02      1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 13        13.21      1, 142, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 14        13.22      1, 142, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 15        13.33      1,  30,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,

 16        13.34      1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 17        13.57      1,  12,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 18        13.58      1,  12,  20, 124, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 19        13.58      1,  12,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 20        13.59      1,  12,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,

 21        13.61      1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,
 22        13.94      1,  70,  80, 160, 200, 210, 220, 230, 240, 250, 260,
 23        14.14      1,  70,  80, 161, 200, 210, 220, 230, 240, 250, 260,
 24        14.14      1,  17,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 25        14.15      1,  31,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,
                         SHORTEST PATHS THROUGH NETWORK
                                   RUN # 4

  PATH        TOTAL                            NODES ON PATH
 NUMBER       COST
-----------------------------------------------------------------------------------------

    1          8.83        1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
    2          8.84        1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
    3         11.19        1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,
    4         11.50        1,  70,  80, 163, 200, 210, 220, 230, 240, 250, 260,
    5         11.88        1,  70,  80, 165, 200, 210, 220, 230, 240, 250, 260,

    6         11.98        1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
    7         12.70        1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
    8         12.84        1, 141, 150, 183, 200, 210, 220, 230, 240, 250, 260,
    9         12.85        1, 141, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   10         12.98        1,  70,  80, 166, 200, 210, 220, 230, 240, 250, 260,

   11         13.01        1,  12,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   12         13.02        1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   13         13.21        1, 142, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   14         13.22        1, 142, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   15         13.33        1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,

   16         13.33        1,  30,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   17         13.34        1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   18         13.57        1,  12,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   19         13.58        1,  12,  20, 124, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   20         13.58        1,  12,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,

   21         13.59        1,  12,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   22         13.62        1,  31,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   23         13.63        1,  31,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   24         13.73        1,  33,  40, 132, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   25         13.74        1,  33,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
                         SHORTEST PATHS THROUGH NETWORK
                                   RUN # 5

 PATH      TOTAL                        NODES ON PATH
NUMBER     COST
------------------------------------------------------------------------------------

   1       7.88      1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   2       8.15      1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   3       8.73      1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   4       8.82      1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   5       8.92      1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

   6       9.00      1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   7       9.02      1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
   8       9.06      1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   9       9.10      1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  10       9.16      1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  11       9.20      1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  12       9.26      1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  13       9.31      1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  14       9.33      1,  13,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  15       9.35      1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,

  16       9.35      1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  17       9.36      1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,
  18       9.41      1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  19       9.41      1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  20       9.43      1,  11,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  21       9.46      1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  22       9.51      1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,
  23       9.51      1,  11,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  24       9.53      1,  14,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  25       9.56      1,  13,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,
                          SHORTEST PATHS THROUGH NETWORK
                                     RUN # 6

 PATH      TOTAL                         NODES ON PATH
NUMBER     COST
------------------------------------------------------------------------------------

   1        6.21     1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   2        6.48     1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   3        7.35     1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
   4        7.68     1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
   5        7.84     1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,

   6        8.48     1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   7        8.76     1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   8        8.81     1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   9        8.82     1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  10        8.92     1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  11        9.09     1,  13,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  12        9.10     1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  13        9.16     1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  14        9.16     1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  15        9.20     1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  16        9.26     1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  17        9.31     1,  13,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  18        9.31     1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  19        9.35     1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  20        9.36     1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,

  21        9.40     1,  13,  20, 102, 110, 172, 200, 210, 220, 230, 240, 250, 260,
  22        9.41     1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  23        9.43     1,  11,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  24        9.46     1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  25        9.51     1,  11,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
                SHORTEST PATHS THROUGH NETWORK
                           RUN # 7

  PATH      TOTAL                       NODES ON PATH
 NUMBER     COST
-------------------------------------------------------------------------------

    1       5.93     1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
    2       6.20     1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
    3       7.07     1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
    4       7.40     1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
    5       7.56     1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,

    6       8.44     1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
    7       8.71     1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
    8       8.77     1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
    9       8.82     1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   10       8.92     1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

   11       9.05     1,  13,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   12       9.10     1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   13       9.12     1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
   14       9.16     1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   15       9.20     1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,

   16       9.26     1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   17       9.27     1,  13,  20, 124, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   18       9.31     1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   19       9.35     1,  30,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   20       9.36     1,  13,  20, 102, 110, 172, 200, 210, 220, 230, 240, 250, 260,

   21       9.36     1,  70,  80, 162, 200, 210, 220, 230, 240, 250, 260,
   22       9.39     1,  31,  40, 132, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   23       9.41     1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   24       9.43     1,  11,  20, 122, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   25       9.46     1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
                         SHORTEST PATHS THROUGH NETWORK
                                    RUN # 8

 PATH      TOTAL                          NODES ON PATH
NUMBER     COST
-----------------------------------------------------------------------------------------

   1       6.09       1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   2       6.11       1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   3       6.16       1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   4       6.19       1,  31,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   5       6.23       1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

   6       6.31       1,  33,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   7       6.33       1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   8       6.38       1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   9       6.43       1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  10       6.44       1,  30,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  11       6.45       1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  12       6.47       1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  13       6.50       1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  14       6.52       1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  15       6.54       1,  31,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  16       6.55       1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  17       6.59       1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  18       6.60       1,  14,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  19       6.64       1,  30,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  20       6.65       1,  14,  20, 101, 110, 173, 200, 210, 220, 230, 240, 250, 260,

  21       6.65       1,  11,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  22       6.67       1,  33,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  23       6.67       1,  14,  20, 123, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  24       6.68       1,  91, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  25       6.69       1, 140, 150, 183, 200, 210, 220, 230, 240, 250, 260,
                          SHORTEST PATHS THROUGH NETWORK
                                    RUN # 9

 PATH       TOTAL                            NODES ON PATH
NUMBER      COST
-----------------------------------------------------------------------------------------------

   1        5.62     1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   2        5.98     1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   3        6.05     1,  31,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   4        6.06     1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   5        6.09     1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,

   6        6.11     1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   7        6.15     1,  33,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   8        6.16     1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   9        6.18     1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  10        6.33     1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  11        6.33     1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  12        6.38     1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  13        6.40     1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
  14        6.40     1,  31,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  15        6.42     1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,

  16        6.42     1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  17        6.43     1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  18        6.44     1,  30,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  19        6.45     1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  20        6.47     1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  21        6.51     1,  33,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  22        6.52     1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  23        6.55     1,  12,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  24        6.55     1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  25        6.59     1,  13,  20, 101, 110, 173, 200, 210, 220, 230, 240, 250, 260,
                         SHORTEST PATHS THROUGH NETWORK
                                    RUN # 10

 PATH      TOTAL                          NODES ON PATH
NUMBER     COST
------------------------------------------------------------------------------------------

  1        5.12      1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  2        5.48      1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  3        5.68      1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  4        5.90      1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
  5        5.91      1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,

  6        5.93      1,  31,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  7        5.99      1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  8        6.02      1,  33,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  9        6.09      1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 10        6.11      1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

 11        6.16      1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 12        6.25      1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 13        6.29      1,  31,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 14        6.33      1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 15        6.34      1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,

 16        6.38      1,  33,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 17        6.38      1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 18        6.43      1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 19        6.44      1,  30,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 20        6.45      1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

 21        6.47      1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 22        6.48      1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,
 23        6.48      1,  31,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
 24        6.52      1,  11,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 25        6.52      1,  13,  20, 101, 110, 173, 200, 210, 220, 230, 240, 250, 260,
                         SHORTEST PATHS THROUGH NETWORK
                                   RUN # 11

 PATH      TOTAL                            NODES ON PATH
NUMBER     COST
-------------------------------------------------------------------------------------

   1       4.84     1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   2       5.20     1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   3       5.40     1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
   4       5.62     1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
   5       5.64     1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,

   6       5.83     1,  31,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   7       5.91     1,  33,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   8       5.95     1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   9       6.09     1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  10       6.11     1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  11       6.16     1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  12       6.19     1,  31,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  13       6.21     1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  14       6.27     1,  33,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  15       6.30     1,  13,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  16       6.33     1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  17       6.38     1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  18       6.38     1,  31,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  19       6.43     1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  20       6.43     1,  13,  20, 102, 110, 173, 200, 210, 220, 230, 240, 250, 260,

  21       6.44     1,  30,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  22       6.45     1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  23       6.47     1,  33,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  24       6.47     1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  25       6.48     1,  13,  20, 101, 110, 173, 200, 210, 220, 230, 240, 250, 260,
                         SHORTEST PATHS THROUGH NETWORK
                                   RUN # 12

  PATH     TOTAL                              NODES ON PATH
 NUMBER    COST
-----------------------------------------------------------------------------------------------

   1       4.84      1,  31,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   2       4.92      1,  33,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   3       5.11      1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   4       5.15      1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   5       5.16      1,  31,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,

   6       5.19      1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   7       5.22      1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   8       5.23      1,  31,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   9       5.24      1,  33,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  10       5.28      1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  11       5.30      1,  31,  40, 134, 150, 181, 200, 210, 220, 230, 240, 250, 260,
  12       5.31      1,  33,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  13       5.33      1,  31,  40, 134, 150, 180, 200, 210, 220, 230, 240, 250, 260,
  14       5.36      1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  15       5.38      1,  33,  40, 134, 150, 181, 200, 210, 220, 230, 240, 250, 260,

  16       5.38      1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  17       5.39      1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  18       5.40      1,  14,  20, 101, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  19       5.41      1,  33,  40, 134, 150, 180, 200, 210, 220, 230, 240, 250, 260,
  20       5.43      1,  14,  20, 123, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,

  21       5.46      1,  30,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  22       5.49      1,  91, 110, 173, 200, 210, 220, 230, 240, 250, 260,
  23       5.50      1, 140, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  24       5.50      1,  14,  20, 123, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  25       5.51      1,  11,  20, 101, 110, 173, 200, 210, 220, 230, 240, 250, 260,
                          SHORTEST PATHS THROUGH NETWORK
                                     RUN # 13

  PATH      TOTAL                              NODES ON PATH
 NUMBER     COST
------------------------------------------------------------------------------------------

    1       4.79     1,  31,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
    2       4.86     1,  33,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
    3       5.11     1,  31,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
    4       5.11     1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
    5       5.15     1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,

    6       5.18     1,  33,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
    7       5.18     1,  31,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
    8       5.19     1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
    9       5.19     1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   10       5.22     1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

   11       5.24     1,  31,  40, 134, 150, 181, 200, 210, 220, 230, 240, 250, 260,
   12       5.25     1,  33,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   13       5.28     1,  31,  40, 134, 150, 180, 200, 210, 220, 230, 240, 250, 260,
   14       5.28     1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   15       5.32     1,  33,  40, 134, 150, 181, 200, 210, 220, 230, 240, 250, 260,

   16       5.35     1,  33,  40, 134, 150, 180, 200, 210, 220, 230, 240, 250, 260,
   17       5.36     1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   18       5.38     1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   19       5.38     1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   20       5.39     1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,

   21       5.40     1,  14,  20, 101, 110, 173, 200, 210, 220, 230, 240, 250, 260,
   22       5.43     1,  14,  20, 123, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
   23       5.46     1,  30,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
   24       5.48     1,  13,  20, 101, 110, 173, 200, 210, 220, 230, 240, 250, 260,
   25       5.49     1,  91, 110, 173, 200, 210, 220, 230, 240, 250, 260,
                        SHORTEST PATHS THROUGH NETWORK
                                  RUN # 14

 PATH     TOTAL                            NODES ON PATH
NUMBER    COST
------------------------------------------------------------------------------------------------

   1      4.74     1,  31,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   2      4.81     1,  33,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   3      4.88     1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   4      5.06     1,  31,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
   5      5.11     1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,

   6      5.12     1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
   7      5.12     1,  33,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
   8      5.13     1,  31,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
   9      5.15     1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  10      5.19     1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,

  11      5.19     1,  31,  40, 134, 150, 181, 200, 210, 220, 230, 240, 250, 260,
  12      5.20     1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  13      5.20     1,  33,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  14      5.22     1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  15      5.23     1,  31,  40, 134, 150, 180, 200, 210, 220, 230, 240, 250, 260,

  16      5.26     1,  33,  40, 134, 150, 181, 200, 210, 220, 230, 240, 250, 260,
  17      5.27     1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,
  18      5.28     1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  19      5.29     1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  20      5.30     1,  33,  40, 134, 150, 180, 200, 210, 220, 230, 240, 250, 260,

  21      5.33     1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,
  22      5.37     1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
  23      5.38     1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  24      5.39     1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  25      5.40     1,  14,  20, 101, 110, 173, 200, 210, 220, 230, 240, 250, 260,
                     SHORTEST PATHS THROUGH NETWORK
                                RUN # 15

PATH      TOTAL                          NODES ON PATH
NUMBER    COST
------------------------------------------------------------------------------------

  1       4.60      1, 143, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  2       4.70      1,  31,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  3       4.76      1,  33,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  4       4.92      1, 143, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  5       4.99      1, 143, 150, 183, 200, 210, 220, 230, 240, 250, 260,

  6       5.01      1,  31,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
  7       5.05      1, 143, 150, 181, 200, 210, 220, 230, 240, 250, 260,
  8       5.07      1,  13,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
  9       5.08      1,  33,  40, 134, 150, 184, 185, 200, 210, 220, 230, 240, 250, 260,
 10       5.09      1,  31,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,

 11       5.09      1, 143, 150, 180, 200, 210, 220, 230, 240, 250, 260,
 12       5.11      1,  14,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 13       5.15      1,  30,  40, 134, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 14       5.15      1,  33,  40, 134, 150, 183, 200, 210, 220, 230, 240, 250, 260,
 15       5.15      1,  31,  40, 134, 150, 181, 200, 210, 220, 230, 240, 250, 260,

 16       5.19      1, 140, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 17       5.19      1,  31,  40, 134, 150, 180, 200, 210, 220, 230, 240, 250, 260,
 18       5.21      1,  33,  40, 134, 150, 181, 200, 210, 220, 230, 240, 250, 260,
 19       5.22      1,  11,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 20       5.24      1,  13,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,

 21       5.25      1,  33,  40, 134, 150, 180, 200, 210, 220, 230, 240, 250, 260,
 22       5.28      1,  14,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 23       5.37      1,  13,  20, 101, 110, 173, 200, 210, 220, 230, 240, 250, 260,
 24       5.38      1,  10,  20, 123, 150, 185, 200, 210, 220, 230, 240, 250, 260,
 25       5.39      1,  11,  20, 122, 150, 185, 200, 210, 220, 230, 240, 250, 260,
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